IEEE Vision for Smart Grid Controls: 2030 and Beyond

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# Table of Contents

Chapter 1  
Introduction .................................................................................................................. 1  
1.1 Citations.................................................................................................................... 3

Chapter 2  
Overview of Existing Control Practice in the Electric Power Grid ............................. 4  
2.1 Introduction .............................................................................................................. 4  
2.2 Generation set point control for markets and economic dispatch .......................... 5  
2.3 Beyond set point control: stable power and frequency regulation ....................... 8  
2.4 Electromechanical dynamics of primary and secondary control ......................... 9  
2.5 Reactive power and voltage magnitude control ..................................................... 16  
2.6 Communication, measurement and computational architectures supporting present day grid control ................................................................. 17  
2.7 Interdependencies with other cyber and digital infrastructures ............................ 20  
2.8 Summary ................................................................................................................ 22  
2.9 Citations.................................................................................................................... 22

Chapter 3  
Drivers for Change ........................................................................................................ 24  
3.1 Introduction .............................................................................................................. 24  
3.2 Driver 1: Decarbonization ..................................................................................... 25  
3.3 Driver 2: Reliability in the face of growing demand ............................................. 27  
3.4 Driver 3: Electrification of transportation ............................................................. 32  
3.5 Driver 4: Empowered consumers ....................................................................... 35  
3.6 Driver 5: Market designs and regulatory paradigms .......................................... 37  
3.7 Challenges ............................................................................................................. 39  
3.8 Enabling factors .................................................................................................... 40  
3.9 Summary ................................................................................................................ 49  
3.10 Citations................................................................................................................... 50

Chapter 4  
Control-enabled Smart Grid: Scenarios for 2030 to 2050 .......................................... 53  
4.1 Introduction .............................................................................................................. 53  
4.2 Scenario 1: Grid-scale real-time endpoint-based control .................................... 54  
4.3 Scenario 2: Dynamic pricing and multiple-horizon power markets .................... 59  
4.4 Scenario 3: Real-time, closed-loop, ubiquitous demand response ....................... 62  
4.5 Scenario 4: Smart periphery—coordinated and hierarchical microgrids ............ 66  
4.6 Scenario 5: Transportation electrification ............................................................ 69  
4.7 Scenario 6: Distribution automation .................................................................... 73  
4.8 Scenario 7: AC-DC transmission systems ............................................................ 76  
4.9 Scenario 8: Renewable generation ...................................................................... 80  
4.10 Conclusions .......................................................................................................... 83
# Table of Contents

4.11 Citations .......................................................................................................................... 83

## Chapter 5

### Research Challenges ......................................................................................................... 85

5.1 Introduction ................................................................................................................... 85
5.2 Loci of control: innovations in current power systems ...................................................... 86
5.3 Loci of control: emerging centers of activity ................................................................. 103
5.4 Loci of control: grid-wise perspectives ......................................................................... 119
5.5 Loci of control: game-changing control architectures .................................................... 126
5.6 Emerging control themes ............................................................................................. 130
5.7 Concluding remarks ....................................................................................................... 135
5.8 Citations ......................................................................................................................... 136

## Chapter 6

### Concluding Remarks ....................................................................................................... 144

6.1 Citations .......................................................................................................................... 146
## Acronyms and Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-AGC</td>
<td>adaptive automatic generation control</td>
</tr>
<tr>
<td>AC</td>
<td>alternating current</td>
</tr>
<tr>
<td>ACE</td>
<td>area control error</td>
</tr>
<tr>
<td>ADC</td>
<td>analog-to-digital converter</td>
</tr>
<tr>
<td>ADR</td>
<td>automated demand response</td>
</tr>
<tr>
<td>AGC</td>
<td>automatic generation control</td>
</tr>
<tr>
<td>AMI</td>
<td>advanced metering infrastructure</td>
</tr>
<tr>
<td>APC</td>
<td>active power control</td>
</tr>
<tr>
<td>AS</td>
<td>ancillary service</td>
</tr>
<tr>
<td>AT&amp;C</td>
<td>aggregate technical and commercial</td>
</tr>
<tr>
<td>ATC</td>
<td>available transfer capabilities</td>
</tr>
<tr>
<td>CAISO</td>
<td>California Independent System Operator</td>
</tr>
<tr>
<td>CAP</td>
<td>switched capacitor</td>
</tr>
<tr>
<td>C&amp;I</td>
<td>commercial and industrial</td>
</tr>
<tr>
<td>CCS</td>
<td>carbon capture and storage</td>
</tr>
<tr>
<td>CCHP</td>
<td>combined cooling, heating and power</td>
</tr>
<tr>
<td>CFE</td>
<td>Comisión Federal de Electricidad (English: Federal Electricity Commission)</td>
</tr>
<tr>
<td>CHP</td>
<td>combined heat and power</td>
</tr>
<tr>
<td>CIN/SI</td>
<td>complex interactive networks/systems initiative</td>
</tr>
<tr>
<td>CSP</td>
<td>concentrated solar plant</td>
</tr>
<tr>
<td>CT</td>
<td>combustion turbine</td>
</tr>
<tr>
<td>DA</td>
<td>distribution automation</td>
</tr>
<tr>
<td>DAC</td>
<td>digital-to-analog converter</td>
</tr>
<tr>
<td>DAE</td>
<td>differential algebraic equation</td>
</tr>
<tr>
<td>DAM</td>
<td>day-ahead market</td>
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<tr>
<td>DC</td>
<td>direct current</td>
</tr>
<tr>
<td>DCS</td>
<td>distributed control system</td>
</tr>
<tr>
<td>DER</td>
<td>distributed energy resource</td>
</tr>
<tr>
<td>DESD</td>
<td>distributed energy storage device</td>
</tr>
<tr>
<td>DFIG</td>
<td>doubly fed induction generator</td>
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</tbody>
</table>
# Acronyms and Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>DG</td>
<td>distributed generation</td>
</tr>
<tr>
<td>DR</td>
<td>demand response</td>
</tr>
<tr>
<td>DRER</td>
<td>distributed renewable energy resource</td>
</tr>
<tr>
<td>DSTATCOM</td>
<td>distribution static synchronous compensator</td>
</tr>
<tr>
<td>DSM</td>
<td>demand-side management</td>
</tr>
<tr>
<td>EMS</td>
<td>energy management system</td>
</tr>
<tr>
<td>EPRI</td>
<td>Electric Power Research Institute</td>
</tr>
<tr>
<td>ERCOT</td>
<td>Electric Reliability Council of Texas</td>
</tr>
<tr>
<td>ERP</td>
<td>enterprise resource planning</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>EV</td>
<td>electric vehicle</td>
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<tr>
<td>FACTS</td>
<td>flexible alternating current transmission system</td>
</tr>
<tr>
<td>FDIR</td>
<td>fault detection isolation and restoration</td>
</tr>
<tr>
<td>FERC</td>
<td>Federal Energy Regulatory Commission</td>
</tr>
<tr>
<td>FID</td>
<td>fault isolation device</td>
</tr>
<tr>
<td>FIDVR</td>
<td>fault induced delayed voltage recovery</td>
</tr>
<tr>
<td>GTO</td>
<td>gate turn-off</td>
</tr>
<tr>
<td>HESS</td>
<td>hybrid energy storage system</td>
</tr>
<tr>
<td>HV</td>
<td>high voltage</td>
</tr>
<tr>
<td>HVAC</td>
<td>heating, ventilation and air conditioning</td>
</tr>
<tr>
<td>HVDC</td>
<td>high-voltage direct current</td>
</tr>
<tr>
<td>ICT</td>
<td>information and communication technology</td>
</tr>
<tr>
<td>IED</td>
<td>intelligent electronic device</td>
</tr>
<tr>
<td>IGBT</td>
<td>insulated gate bipolar transistor</td>
</tr>
<tr>
<td>IGCC</td>
<td>integrated gasification combined cycle</td>
</tr>
<tr>
<td>IPP</td>
<td>independent power producer</td>
</tr>
<tr>
<td>ISO</td>
<td>independent system operator</td>
</tr>
<tr>
<td>LED</td>
<td>light-emitting diode</td>
</tr>
<tr>
<td>LMP</td>
<td>locational marginal price</td>
</tr>
<tr>
<td>LV</td>
<td>low voltage</td>
</tr>
<tr>
<td>MISO</td>
<td>Midwest Independent System Operator</td>
</tr>
<tr>
<td>MPC</td>
<td>model predictive control</td>
</tr>
<tr>
<td>MPPT</td>
<td>maximum power point tracking</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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</tr>
<tr>
<td>MW</td>
<td>megawatt</td>
</tr>
<tr>
<td>MV</td>
<td>medium voltage</td>
</tr>
<tr>
<td>NAN</td>
<td>neighborhood-area network</td>
</tr>
<tr>
<td>NERC</td>
<td>North American Reliability Corporation</td>
</tr>
<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology</td>
</tr>
<tr>
<td>OLTC</td>
<td>on-load tap changer</td>
</tr>
<tr>
<td>OPGW</td>
<td>optical ground wire</td>
</tr>
<tr>
<td>PDC</td>
<td>phasor data concentrator</td>
</tr>
<tr>
<td>PEV</td>
<td>plug-in electric vehicle</td>
</tr>
<tr>
<td>PHEV</td>
<td>plug-in hybrid electric vehicle</td>
</tr>
<tr>
<td>PI</td>
<td>proportional-integral</td>
</tr>
<tr>
<td>PLC</td>
<td>power line carrier or programmable logic controller</td>
</tr>
<tr>
<td>PMU</td>
<td>phasor measurement unit or phasor management unit</td>
</tr>
<tr>
<td>PREPA</td>
<td>Puerto Rico Electric Power Authority</td>
</tr>
<tr>
<td>PSS</td>
<td>power system stabilizer</td>
</tr>
<tr>
<td>PV</td>
<td>photovoltaic</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>research and development</td>
</tr>
<tr>
<td>RES</td>
<td>renewable energy source</td>
</tr>
<tr>
<td>RPS</td>
<td>Renewable Portfolio Standard</td>
</tr>
<tr>
<td>RSR</td>
<td>regulation service reserve</td>
</tr>
<tr>
<td>RTM</td>
<td>real-time market</td>
</tr>
<tr>
<td>RTO</td>
<td>regional transmission organization</td>
</tr>
<tr>
<td>RTU</td>
<td>remote terminal unit</td>
</tr>
<tr>
<td>SCADA</td>
<td>supervisory control and data acquisition</td>
</tr>
<tr>
<td>SGIP</td>
<td>Smart Grid Interoperability Panel</td>
</tr>
<tr>
<td>SOC</td>
<td>sensing, optimization, and control</td>
</tr>
<tr>
<td>SQRA</td>
<td>security, quality, reliability, and availability</td>
</tr>
<tr>
<td>SSSC</td>
<td>static series synchronous compensator</td>
</tr>
<tr>
<td>SST</td>
<td>solid-state transformer</td>
</tr>
<tr>
<td>STATCOM</td>
<td>static synchronous compensator</td>
</tr>
<tr>
<td>SVC</td>
<td>static VAR compensator or static voltage compensator</td>
</tr>
<tr>
<td>T&amp;D</td>
<td>transmission and distribution</td>
</tr>
<tr>
<td>TOU</td>
<td>time of use</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
</tr>
<tr>
<td>---------</td>
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</tr>
<tr>
<td>TCSC</td>
<td>thyristor-controlled series compensator</td>
</tr>
<tr>
<td>TSO</td>
<td>transmission system operator</td>
</tr>
<tr>
<td>UAN</td>
<td>user-area network</td>
</tr>
<tr>
<td>UPFC</td>
<td>unified power flow controller</td>
</tr>
<tr>
<td>USC</td>
<td>ultra-supercritical</td>
</tr>
<tr>
<td>UTE</td>
<td>Usinas y Terminales Eléctricas</td>
</tr>
<tr>
<td>VAR</td>
<td>volt-ampere reactive</td>
</tr>
<tr>
<td>VMG</td>
<td>virtual microgrid</td>
</tr>
<tr>
<td>VSAT</td>
<td>very-small-aperture terminal</td>
</tr>
<tr>
<td>VSC</td>
<td>voltage source converter</td>
</tr>
<tr>
<td>WAN</td>
<td>wide-area network</td>
</tr>
<tr>
<td>WAMS</td>
<td>wide-area measurement system</td>
</tr>
</tbody>
</table>
Glossary

active power control (APC): Control of the real power output of a wind turbine or wind farm in order to assist in balancing total power generated on the grid with total power consumed.

advanced metering infrastructure (AMI): A system for measuring individual customers’ electricity consumption at intervals of an hour or less, and communicating that information at frequent intervals to the distribution utility.

automatic generation control (AGC): An automatic system to vary mechanical input to a generator to match small variations in system load.

ancillary services: Services that ensure reliability and support the transmission of electricity from generation sites to customer loads. Such services can include: load regulation, spinning reserve, nonspinning reserve, replacement reserve, and voltage support.

area control error (ACE): A measured signal that is weighted sum of area frequency error and deviations from set point of powers on select transmission lines that carry major power flows in/out of the region of interest.

balancing authority: An entity responsible for balancing generation and load (with specified imports and exports) within a specified geographic region.

congestion: A condition that occurs when insufficient transfer capacity is available to implement all of the preferred schedules for electricity transmission simultaneously. This condition prevents the least-cost set of generators from serving load, causing an increase in the wholesale price of electricity or cost of service at one or more locations in the system.

contingency: An abnormal event in the power system, such as the tripping of a generator or a transmission line.

critical peak pricing: A dynamic pricing plan that combines peak/off-peak time-of-use rates with substantially higher super-peak rates that apply only to peak hours on a limited number of critical days during the year. Critical days typically are announced the day before, on the basis of forecast market conditions.

cyber-physical systems: Physical systems whose function is governed by a networked communication and control system.

day-ahead market (DAM): A financial market in which market participants purchase and sell energy at financially binding day-ahead prices for the following day, and calculated every hour.

demand-response (DR): Customer loads that are responsive to conditions in the electric power system, particularly at peak times.

demand-side management (DSM): The amount of consumer load reduction at the time of system peak due to utility programs that reduce consumer load during many hours of the year. Examples
include utility rebate and shared savings activities for the installation of energy efficient appliances, lighting and electrical machinery, and weatherization materials. This category also includes all other DSM activities, such as thermal storage, time-of-use rates, fuel substitution, measurement and evaluation, and any other utility-administered DSM activity designed to reduce demand, electricity use, or both.

**distributed energy resource:** A small, modular, decentralized, grid-connected or off-grid energy system located in or near the place where energy is used.

**distributed generation (DG):** Small-scale, on-site generation systems owned by entities that are primarily consumers of electricity.

**distribution:** The delivery of energy to retail customers.

**distribution automation:** The application of advanced technology to automate the maintenance, control, and operation of the distribution network.

**distribution system:** The portion of the transmission and facilities of an electric system that is dedicated to delivering electric energy to an end user.

**dynamic pricing:** A regime in which retail customers face energy prices that vary with the contemporaneous cost of generation or state of supply-and-demand conditions in the electric power system. Prices can be based on day-ahead or hour-ahead forecasts of conditions and can change for as few as 60 critical peak hours per year or might change hourly or more often in real-time pricing plans.

**economic dispatch:** The assignment of generating units’ production to minimize overall costs.

**electric power grid:** A system of synchronized power providers and consumers connected by transmission and distribution lines, and operated by one or more control centers.

**electric system reliability:** The degree to which the performance of the elements of the electrical system results in power being delivered to consumers within accepted standards and in the amount desired. Reliability encompasses two concepts: adequacy and security. Adequacy implies that there are sufficient generation and transmission resources installed and available to meet projected electrical demand plus reserves for contingencies. Security implies that the system will remain intact operationally (i.e., will have sufficient available operating capacity) even after outages or other equipment failure. The degree of reliability can be measured by the frequency, duration, and magnitude of adverse effects on consumer service entities, public power districts, public utility districts, municipalities, rural electric cooperatives, and state and federal agencies.

**electric vehicle (EV):** A vehicle that operates by electric power provided by batteries. EVs include both plug-in hybrid electric vehicles and battery electric vehicles but do not include hybrid electric vehicles, which are self-powered and never connected to the electric grid.

**electricity demand:** The rate at which energy is delivered to loads and scheduling points by generation, transmission, and distribution facilities.
energy efficiency, electricity: Refers to programs that are aimed at reducing the energy used by specific end-use devices and systems, typically without affecting the services provided. These programs reduce overall electricity consumption (reported in megawatt hours), often without explicit consideration for the timing of program-induced savings. Such savings are generally achieved by substituting technologically more advanced equipment to produce the same level of end-use services (e.g., lighting, heating, motor drive) with less electricity. Examples include high-efficiency appliances, efficient lighting programs, high-efficiency heating, ventilating, and air conditioning (HVAC) systems or control modifications, efficient building design, advanced electric motor drives, and heat recovery systems.

energy management system (EMS): The suite of software and hardware that supports a regional control center in managing the production, purchasing, transmission, distribution, and sale of electrical energy in the power system at a minimal cost with respect to safety and reliability.

flexible alternating current transmission system (FACTS): A set of technologies employing power electronics that enable control of various transmission system operating parameters, including volt-ampere-reactive support and power flow.

generation: The process of producing electric energy by transforming other forms of energy; also, the amount of electric energy produced, expressed in kilowatt-hours.

governor droop control: A feedback loop that measures the individual generator’s rotational speed/frequency as output, and modifies prime mover mechanical power in response.

high-voltage direct current (HVDC): Technologies for transmitting bulk power by direct current at transmission-level voltages.

independent power producer: A nonpublic entity that owns facilities to generate electricity for sale to utilities, end users, or both.

independent system operator (ISO): A regulated entity without generation or distribution assets that oversees the wholesale electricity market and operates the bulk power system in a particular region.

intermittent resource: An electric generating plant with output controlled by the natural variability of the energy resource rather than dispatched based on system requirements. Intermittent output usually results from the direct, nonstored conversion of naturally occurring energy fluxes such as solar energy or wind energy.

inverter: A power electronic system whose function is to convert electric power from direct current to alternating current.

islanding: The process by which the power network automatically responds by breaking into self-contained islands when major disruptions occur on a power system, according to fixed procedures that have been established well in advance.

load (electric): The amount of electric power delivered or required at any specific point or points on a system. The requirement originates at the energy-consuming equipment of the consumers.
load control program: Demand-response programs that offer customers incentives to reduce their consumption in response to an instruction or signal from the system operator so that the utility can reduce peak demand.

load factor: The ratio between average and peak power.

locaitional marginal price (LMP): For any economic dispatch, the marginal cost of meeting a small increment of load at a particular location; the spot price of electricity at that location.

losses: The difference between generated power and power delivered to the load, typically caused by resistance in transmission lines and transformers and converted to waste heat.

microgrid: A part of an electric power system consisting of distributed generators, loads, and specialized controls that is capable of operating either in parallel with a utility system or as a stand-alone system.

N – 1 contingency analysis: Evaluation of the transmission line and transformer power flows and bus voltages in case of the loss of a single component, such as a particular generator.

off-peak: Periods of relatively low system demand. These periods often occur in daily, weekly, and seasonal patterns, and differ for each individual electric utility.

on-peak: Periods of relatively high system demand. These periods, which differ for each electric utility, often occur in daily, weekly, and seasonal patterns.

outage: The period during which a generating unit, transmission line, or other facility is out of service.

peak demand or peak load: The maximum load during a specified period of time.

phase angle: The time, expressed as an angle, by which a voltage and current waveform, or two voltage or two current waveforms, are shifted relative to each other.

phasor measurement unit (PMU): A device used to measure current, voltage, and frequency every 1/30 (one-thirtieth) of a second or faster in synchronicity with other such measurements across a wide area based on a Global Positioning System time signal.

plug-in hybrid electric vehicle (PHEV): A vehicle with an internal combustion engine as well as batteries that can be charged using an external power source.

power electronics: Electronic circuits that employ switching electronic semiconductor devices, whose function is to control electrical energy and convert it from one form to another (e.g., from alternating current to direct current, or alternating current at one frequency to alternating current at another frequency).

power factor: The ratio of real power to apparent power. Reflects the degree to which a given amount of current is producing useful work.
**power quality:** The extent to which the voltage waveform at a load conforms to the ideal sinusoidal shape and nominal value. Poor power quality is generally the result of loads that draw current that is not sinusoidal (a particular problem with electronically controlled loads) or weak distribution networks producing frequent outages or voltage sags.

**power system stabilizer (PSS):** An auxiliary feedback loop that modulates field voltage in response to measured frequency, with the objective of improving the damping of the oscillatory frequency modes.

**primary governor control:** A corrective feedback that incrementally changes a generator’s power output in response to locally measured frequency/speed error.

**prosumers:** A power consumer who can also function as a power producer.

**reactance:** The property of a conducting device that introduces a phase shift between voltage and current and introduces an impediment to the flow of alternating current.

**reactive power:** Power that exists in AC power systems when reactance is present. Reactive power charges and discharges the energy stored in reactive elements. It does no time-average work, but its presence still contributes to electrical losses and voltage drops.

**real-time market (RTM):** Coordinates the dispatch of generation and demand resources to meet the demand for electricity in real time, calculated every 5 minutes to 15 minutes.

**real-time pricing:** See dynamic pricing.

**regional transmission organization (RTO):** An organization that is responsible for moving electricity over large interstate areas.

**regulation service reserve:** Reserve used for regulation over a five-minute window to meet the required energy balance and preserving power system stability.

**renewable energy resources:** Energy resources that are naturally replenishing but flow-limited. They are virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time. Renewable energy resources include: biomass, hydro, geothermal, solar, wind, ocean thermal, wave action, and tidal action.

**regulation:** Maintaining voltage and frequency within certain bounds. Also refers to the activity of a government agency charged with controlling the behavior of a public utility or other entity.

**renewable Portfolio Standard (RPS):** A state-level requirement that a minimum fraction of in-state electricity consumption correspond to generation from specified renewable technologies, such as wind, solar, or geothermal.

**reserve capacity microgrids:** Microgrids that can be a source of operating reserve for the grid.

**secondary control:** Control that acts on a slower timescale, over a wider region, by modifying (a subset of) generators’ power set points in the region, with the objective of regulating ACE.
**static VAR compensator (SVC):** A power electronics device belonging to the family of devices known as FACTS used for voltage control by injecting and withdrawing reactive power.

**supervisory control and data acquisition (SCADA):** Specialized computer systems that monitor and control industrial processes, including the operation of components of the electric grid, by gathering and analyzing sensor data in near real time.

**synchronized phasor measurement (synchrophasor):** The measurement produced by phasor measurement units; a voltage or current phasor that has been synchronized with other such measurements using a common time signal from the Global Positioning System.

**thermal energy storage:** The storage of heat energy during utility off-peak times at night, for use during the next day without incurring daytime peak electric rates.

**time-of-day pricing:** A special electric rate feature under which the price per kilowatt hour depends on the time of day.

**time-of-use rates:** Rate schedules that establish fixed time periods based on average system load characteristics, across which prices vary. Typical time-of-use tariffs divide weekdays into two or three time periods (peak, off-peak, and perhaps an intermediate block) and assign weekend hours to an off-peak block. Prices increase from off-peak through peak hours, and the entire tariff schedule may change across seasons.

**transmission network:** The part of the power system that carries electric power over moderate to long distance, usually at high voltage.

**unit commitment:** The process of scheduling a generator (unit) to provide energy during a specific time period.

**virtual microgrid:** A cyberspace concept that allows changeable segments of distribution networks to be managed as microgrids.

**volt-ampere reactive (VAR):** The unit used to measure reactive power, which is present in an AC system when current and voltage are out of phase.

**voltage source converter (VSC):** A power electronic device for converting a direct current voltage to an alternating current voltage.

**wide-area measurement systems (WAMS):** A network of devices, usually consisting of phasor measurement units, that measures quantities of interest on the transmission network across a large geographic area in real time.
Chapter 1

Introduction

The Smart Grid is seen as a fundamentally transformative, global imperative for helping the planet deal with its energy and environmental challenges. Environmental stewardship, explosive growth of global energy demand, increasing emphasis on electrified transportation, aging infrastructures, and empowerment of consumers are some of the major drivers that are necessitating this transformation.

On the global canvas, various initiatives are afoot to decrease the carbon footprint. The Renewables Portfolio Standards in the U.S. for example, was established in California in 2002 with a goal of increasing the percentage of renewable energy sources to 20% by 2017 and 33% by 2020 [3]. In Europe, the target is to raise the penetration from current levels of 20% to about 50% by 2050 [4].

World over, electricity demand is projected to double between 2000 and 2030, growing at an annual rate of 2.4%, faster than the projection for any nonrenewable energy source [2]. Electricity’s share of total final energy consumption has steadily increased over the years, with the figures in the U.S. starting at 2% at the beginning of the previous century, to 11% in 1940, to 20% in 1960, and to over 40% today [5]. Electricity demand growth is strongest in developing countries, where demand will climb by over 4% per year over the projection period, more than tripling by 2030. Consequently, the developing countries’ share of global electricity demand jumps from 27% in 2000 to 43% in 2030 [2]. Growing interest across the globe in electrification of transportation increases these projections further.

There is growing evidence that the U.S. transmission system is in urgent need of modernization. The system has become congested because growth in electricity demand and investment in new generation facilities have not been matched by investment in new transmission facilities. There has been a steady increase in the number of service interruptions on the electricity grid; blackouts result in an estimated $79 billion (approximately 22% of the total revenue for electricity sales) in lost revenue annually. The aging of the electricity infrastructure in the United States exacerbates this problem.

For the purposes of this document, we define a Smart Grid to be an end-to-end cyber-enabled electric power system, from fuel source to generation, transmission, distribution, and end use, that will: 1) enable integration of intermittent renewable energy sources and help decarbonize power systems, 2) allow reliable and secure two-way power and information flows, 3) enable energy efficiency, effective demand management, and customer choice, 4) provide self-healing from power disturbance events, and 5) operate resiliently against physical and cyber attacks.

The path for realizing the Smart Grid is fraught with several formidable challenges. Increased penetration of renewables implies that the transmission systems have to be expanded by a significant amount to support these renewables in dispersed areas. It also introduces operational challenges in
terms of requiring significantly higher levels of regulation and ramping capacity. New flow patterns enter the picture at the distribution level and necessitate drastic changes to the protection, distribution automation, and voltage and VAR management. Increased renewable generation also implies limited dispatchability and increased intermittencies, which are concomitant with increased ancillary services. Increased demand the world over, including the anticipated rapid increase in electrification of transportation, will lead to significant new loads on distribution networks, many of which are woefully inadequate when it comes to monitoring and automation.

*Control* is poised to rise to the occasion and counter a significant number of these challenges. This rise is possible because advances in sensing technologies are making new information available about various aspects of the grid, and progress in communication technologies are making them available at pertinent locations. Decision making, in an automated manner, is therefore becoming feasible, from seconds to seasons, at desired, new, and distributed locations, thereby facilitating a variety of opportunities for control—for reducing consumption, for better exploiting renewable sources, and for increasing the reliability and performance of the transmission and distribution networks. Emerging paradigms of demand response are dramatically altering the picture of loads, allowing them to not simply be followed but shaped. Plug-in electrical vehicles can be viewed not as loads, but as dispatchable assets coming to the aid of the distribution system. Spurred by large-scale experimental and commercial projects, energy storage technologies are rapidly becoming viable alternatives to conventional fossil fuel-based spinning reserves. Each of these factors is making available the use of such information, at pertinent locations, to the relevant decision maker in the grid, thereby bringing control and automation to center stage.

The increased deployment of feedback and communication implies that loops are being closed where they have never been closed before, across multiple temporal and spatial scales, thereby creating a gold mine of opportunities for control. Control systems are needed to facilitate decision making under myriad uncertainties, across broad temporal, geographical, and industry scales—from devices to power system–wide, from fuel sources to consumers, and from utility pricing to demand response. The various challenges introduced can be posed as a system-of-systems problem, necessitating new control themes, architectures, and algorithms. These architectures and algorithms need to be designed so that they embrace the resident complexity in the grid: large-scale, distributed, hierarchical, stochastic, and uncertain. With information and communication technologies and advanced power electronics providing the infrastructure, these architectures and algorithms will need to provide the smarts and use all advances in communications and computation such as 4G networks, cloud computing, and multiple-core processors.

This document highlights the role of control systems in the evolution of the Smart Grid. It includes an overview of research investigations that are needed for renewable integration, reliability, self-healing, energy efficiency, and resilience to physical and cyber attacks. These investigations are encapsulated in several loci of control including: new methodologies for transmission, distribution, and renewable energy, and storage; new roles in emerging topics such as electricity markets, demand response, microgrids, and virtual power plants; and new solutions for efficiency, heating and cooling, and security. Together, they usher in new horizons for control, such as architecting a system of distributed systems, building interfaces to social sciences such as economics, sociology, and psychology, and providing a blueprint for critical infrastructure systems. Although the emerging role of control and its implication on grid architectures have been articulated in papers [1, 6], a comprehensive discourse on the evolution of Smart Grid and the opportunities and challenges that it presents for control, ranging from generators to consumers, from planning to real-time operation, from current practice to
scenarios in 2050 in the grid and all of its subsystems, has not been undertaken hitherto and is the purpose of this document.

We begin with current practices in Chapter 2, which illustrate the roles of control in power systems such as power balance, frequency regulation, and reactive power control. Chapter 3 discusses drivers for change that pave the way for a paradigm shift in the electric grid. Chapter 4 presents different scenarios of the Smart Grid that might emerge three decades from now. Chapter 5 delineates research challenges across the entire grid and the emerging control themes. Conclusions are found in Chapter 6.

1.1 Citations


Chapter 2  Overview of Existing Control Practice in the Electric Power Grid

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2.1 Introduction

Electric power grids are among the largest and most complex of all human engineered systems. Through the second half of the twentieth century, many of these systems saw tremendous expansion that established power transmission interconnections over long distances. These interconnects were first developed with a primary goal of mutually reinforcing reliability between regions. With the expansion of wholesale markets for power over the last two decades, long distance transmission ties have increasingly been employed to allow using remote generation resources and to enable economic interchange of power. Driven in part by the desire to integrate new generation sources such as renewables, this trend towards wide-area interconnection is being revisited in the twenty-first century, because significant transmission reinforcement is again being considered in many regions. Moreover, in recent years the physical power flow coupling of the transmission grid has been increasingly supplemented by coupling with high bandwidth, wide-area sensing, communication, and control under the banner of the Smart Grid [11]. Clearly, the objective is to exploit opportunities in control-based cyber-infrastructure to enable more efficient usage of the grid’s high-capital-cost physical infrastructure, to achieve better performance, lower cost, and reduce the environmental impact of our electric energy use.

To put into perspective the promise of the Smart Grid and the potential impact that control can have on it, it is important to understand the underlying dynamics of the power grid and its existing control practice. The goal of this chapter is to provide this perspective on the history and current practice in power grid control. It will broadly focus on four major topics in grid practice today: 1) generation power set point selection through market operations or economic dispatch, 2) primary and secondary control for frequency regulation and power balance, 3) reactive power control for regulation of
voltage magnitudes, and 4) Communication and sensing technologies to support these control functions.

The electric power grid has long provided a very challenging and fruitful engineering application for the interrelated tools of dynamical systems analysis, control system design, and optimization [2]. Through the transfer of power through long-distance, high-voltage transmission, power grids can display dynamic electromechanical coupling on a nearly continental scale, and the mix of near-speed-of-light electrical phenomena with mechanical response of generators and load means that major disturbances can propagate over long distances, at speeds of many hundreds to thousands of miles per second. At slower timescales, the fact that the characteristics and cost of grid operations depend heavily on the geographic mix of generation and load implies that considerable attention is devoted to periodic updates of the set points of many thousands of pieces of equipment throughout the network. Therefore, control, as interpreted in power systems applications, must be understood in a very broad context. Unlike many simpler engineered systems, control for the grid is not only a problem in feedback design to achieve regulation, desirable dynamic response characteristics, or both, but also the selection of the quasi–steady state or steady-state operating point as determined by the grid’s nonlinear power flow equations of equilibrium.

2.2 Generation set point control for markets and economic dispatch

Among the key input quantities that determine the steady state operating point of an electric power grid are the injected powers from generators (called the generation dispatch in power systems parlance [12]) and the electrical power demand, typically aggregated at distribution substations that constitute major load connection points to the grid. Historically, load has largely been treated as an uncontrolled, exogenous input, and electric utilities have been operated with an assumed “obligation to serve,” in which generation would be operated to meet this exogenous load demand at all times. Even in the simplest perspective on grid operations, it is clear that this operating philosophy imposes a fundamental control requirement: the sum of the power output levels of generators must be regulated to match the total load plus losses on the grid. Details of how this balance is maintained on a very fast timescale will follow, but it is helpful to consider first the simpler, quasi–steady state problem: given an estimate of load demand, how might one choose generator power output levels from among a fleet of many such units. In practice, this problem is indeed solved on a periodic basis, on timescales of minutes, to select desired set points for generator output. (Faster dynamics and load variation might, of course, induce deviations from set point.) In grid operations in which fossil-fueled generators are a significant percentage of the fleet, which has historically been true for most systems around the world, choice of generation dispatch has a huge impact on per unit time cost of power production. Hence, this periodic operating point update is typically posed as an optimization problem. Through electricity restructuring over the past two decades, in much of North America and many other parts of the world, this optimization is increasingly addressed by power markets. In the U.S., such markets are often coordinated and managed by regional entities called independent system operators (ISO), such as the Midwest Independent System Operator (MISO), PJM Interconnection, and the California Independent System Operator (CAISO). Hence, from the perspective of market operators, a key control objective in the grid is a very high dimensional regulation problem, in which a very large number of generating units are required to stably regulate to new set points of desired megawatt (MW) power output, while maintaining reliable system operation. For example, in the MISO, the market is periodically updated at 5-minute intervals, based on a requirement to meet
current load demand, from bids (i.e., offers to sell) that are submitted by independent generator owners. Such a bid can be thought of as characterizing the dollar per hour ($/hr) offered price for operating a specific MW output level. Recognizing that a market optimization will depend only on incremental cost, these bids are actually characterized by the slope as incremental cost in units of $/hr/MW, or equivalently $/MWhr, versus MW output level. If one considers a simple approximation that treats the grid as lossless and neglects limits on the achievable MW output of an individual unit, it is easy to confirm that a necessary condition for optimal operation is that all incremental costs at every location must be equal.\(^1\) A graphic illustration of the actual outcome of this periodic, market-based update of operating condition can be found in the information displays of ISOs. The MISO maintains a web display that plots a geographic contour of $/MWhr locational marginal price (LMP) [9] across its service area,\(^2\) updated every 5 minutes. Despite the approximations required to support the result of equal $/MWhr price representing market optimum, conditions very close to this ideal are not uncommon in practice. Figure 2.1 provides a graphic illustration of this condition in practice for the MISO service area, showing a nearly uniform price (and hence near-uniform color) in the $20/MWhr to $26/MWhr range over the whole area. However, it is also important to recognize that the market optimization to select the MW power output level of each machine must respect a wide variety of engineering constraints. These constraints might reflect the immediate operating limits of the transmission network or *contingency constraints* that represent the need for the network to continue operating reliably in the face of credible failures of individual pieces of equipment. As operating conditions move to a regime in which one or more of these inequality constraints become active (often under conditions of higher load), the simple uniform price condition no longer holds, and widely differing patterns of locational prices might emerge, as illustrated in Figure 2.2 for August 9, 2011.

\(^1\) The argument supporting this condition may be made by contradiction. Suppose that one claimed an optimal operating condition existed for which two generators had unequal incremental costs. In this case, an arbitrage opportunity to lower costs is guaranteed to exist: one could reduce the generator with higher cost by an increment (e.g., 1 MW), and increase the lower cost unit by an equal increment, and the resulting total $/hr operating cost would have to be reduced.

\(^2\) Implicit in these time-varying geographic contours of power prices are time variations in several hundred commanded generator power outputs, and the independently varying MW power demand of tens of thousands of loads. However, because individual generators’ megawatt power output levels are deemed proprietary production information in a competitive market, these are not publicly reported by MISO.
Figure 2.1 – Periodic market updates determine generators’ MW control set points: near-uniform geographic contours of prices in Midwest U.S., 23:05 EST July 12, 2012 [6]

Figure 2.2 – Periodic market updates determine generators’ MW control set points: high varied geographic contours of prices in Midwest U.S., 13:20 EST August 9, 2011 [6]
2.3 Beyond set point control: Stable power and frequency regulation

In portions of the network that operate with ISOs overseeing wholesale markets with competitive generators, interconnection contracts between the generators and the system operator must specify associated performance requirements that ensure generators meet standards that allow reliable grid operation, for which the ISO is responsible. In regions operating as vertically integrated monopolies, responsibility for generation operation and transmission grid operation lies with a single entity. In either organizational structure, requirements on generators will include specification of control regulation performance: how quickly and how precisely a generator must achieve the MW power output determined either by the ISO’s periodic market update, or by a similar periodic update to a lowest cost dispatch for a vertically integrated utility.

This aspect of control, that of an individual generator achieving its market or optimization-commanded set point of MW output, can be seen largely as a requirement on each individual piece of equipment, albeit influenced by its terminal coupling to the grid. If this were the extent of the grid control problem, the challenge might appear modest. However, a huge element of the control challenge is embedded in the qualifiers on the regulation requirement: that the generating units must stably regulate to their new commanded set point, while maintaining reliable, secure system operation. Determination of system-wide stability properties is heavily influenced by the nature of both continuously acting and discrete control systems throughout the network. The requirement of reliability adds a huge number of scenario-based analyses. Not only must the system maintain stability for the current operating point, but also meet some standards that are enforced by the North American Reliability Corporation (NERC) and the Federal Energy Regulatory Commission (FERC) in the U.S., which are that it be $N-1$ secure. Roughly speaking, $N-1$ security requires that the grid must maintain acceptable operation in the face of a large number of credible equipment failure scenarios, which often start from a minimum set in which the system must stably “ride through” the loss of any one piece of equipment, up to the largest generator or most heavily loaded transmission line (hence the terminology: over $N$ network elements, the system must survive the loss of any single piece). From a control analysis standpoint, this specification is a large-scale robust stability requirement: stability must be maintained for every member of a family of systems, each representing a different discontinuous structural change to the nominal, undegraded system. A typical dynamic model for a power system is a mixed system of nonlinear differential-algebraic equations governing its dynamic response. Hence, these requirements bring in much more complex, large-scale system challenges inherent in operating the power grid, as their satisfaction involves not only the control systems of the individual generators, but also of the transmission network, and of a wide range of other grid equipment and load characteristics. Hence the problem of guaranteeing robust stability is assuredly NP-hard, and pragmatic heuristics that perform exhaustive (approximate) tests over a manageable number of contingency scenarios are the normal practice in the industry today [8].

As will be explored in subsequent chapters, the premise of the Smart Grid is that enhanced communication and computation will allow future power grids to greatly expand the numbers and classes of equipment productively contributing to control. Properly implemented, more distributed control involving larger numbers of contributors carry great promise to improve the stability, reliability, and economy, and to reduce environmental impact of grid operation. However, it must be recognized that with this promise for improved performance comes the potential for greatly expanded complexity in the problem of assessing and maintaining the robust stability of grid control.
2.4 Electromechanical dynamics of primary and secondary control

Although a comprehensive examination of grid dynamics is beyond the scope of this document, an understanding of the basic characteristics influencing power systems control is helpful and can be briefly summarized. The underlying dynamics of the power grid (the plant, in classical control design parlance) have many facets, but perhaps foremost among these are those governing coupled electromechanical behavior among synchronous generators and their relation to grid frequency [1]. At bus locations with generators attached, the inherent physics of the synchronous machine dictate that the electrical frequency of the generator voltage and the mechanical rotational speed of the generator are locked in fixed proportion to one another so that variation of frequency at these locations directly reflects deviations in rotational speed away from the desired steady state. Moreover, the nature of alternating current (AC) power transmission is such that a synchronous region is in exact equilibrium only if electrical frequency is equal at every node in the network (i.e., all interconnected generators rotating at the same, or nominal, speed). In these basic facts, two related facets of an underlying grid control problem present themselves: 1) The requirement for stable dynamic performance, such that any deviation of the (dynamically) independent frequencies of generators converge to steady state in a stable fashion; and 2) The quasi–steady state regulation requirement that the shared synchronous frequency (equal at all nodes in equilibrium) be regulated to a tight band about its desired 60 Hz (hertz) value. These requirements suggest added feedback control functions, in addition to that of holding generator MW output to its economically determined set point. In present day practice, these are broadly classified into categories called primary governor control, and secondary control [5, 12]. As will be explored in more detail in the following subsections, primary governor control is a corrective feedback (often just a proportional gain) that incrementally changes a generator’s power output in response to locally measured frequency/speed error. Secondary control acts on a slower timescale, over a wider region, by modifying a subset of generators’ power set points in the region, with the objective of regulating a measured signal called the area control error (ACE). The ACE signal comprises a weighted sum of area frequency error and deviations from set point (scheduled interchange) of powers on select transmission lines that carry major power flows in/out of the region of interest.

The requirement for stably regulating frequency within a tight range reflects the objective to reliably maintain the instantaneous balance between generation and load. This goal is accomplished by ensuring that adequate resources (i.e., generators with megawatt output that can be varied) are available to respond to expected and unexpected imbalances, and to restore frequency to its scheduled value in order to ensure uninterrupted electric supply. The rotational inertia of traditional synchronous generators and its coupling to the electrical terminal behavior of the machine plays a significant role in defining the underlying dynamics that must be stably controlled. Hence, it is worthwhile to provide a brief overview of these dynamics. To understand the underlying behavior requires no more than a very basic understanding of physics, an understanding of some inherent features of synchronous machine behavior, and a simple approximation that follows from operating practice in the power grid.

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3 In the terminology of the power grid, a bus is point of connection for generation, load, or multiple transmission lines. Neglecting details relating to substation switching, a bus can be understood simply to be a network node in the electrical circuit formed by the bulk transmission system.
First, one observes that as a rotating mass, a synchronous generator-turbine set satisfies the rotational form of Newton’s law:

\[
[\text{rotational inertia}] \times [\text{rotational acceleration}] = [\text{net applied torque}]
\]

Our second observation is that in a rotating frame, power equals the product of torque times speed, or equivalently (up to a multiplicative constant), torque times electrical frequency. If one further recognizes that frequency is successfully regulated to an exceptionally tight band (deviations greater that ± 0.5% are quite uncommon in the Eastern Interconnection of North America), power can then be very well-approximated as proportional to torque. Hence, in a normalized system of units, power and torque can be approximated as interchangeable. The remaining observations then follow from inherent features of synchronous generators. As reflected in the name, the electrical frequency of generator terminal voltage is exactly synchronized to rotational speed. That is, up to a constant determined by the number of poles fixed by the machine design, rotational speed and electrical frequency are exactly proportional; again, in the normalized, per-unit quantities typically used in grid analysis, they can be used interchangeably. Hence, in the rotational form of Newton’s law, time rate of change of electrical frequency can be substituted for rotational acceleration. Moreover, modern synchronous generators are exceptionally efficient in their conversion of applied mechanical shaft power to electrical power output, with very low internal losses. As a consequence, the torque opposing motion created by the magnetic fields in the windings of the machine, when multiplied by rotational speed, is essentially equal to the electrical power output. In our constant rotational speed approximation\(^4\) that treats torque and power interchangeably—electrical output power is equivalent to a torque contribution acting to decelerate the machine. Conversely, the mechanical shaft power from the prime mover (e.g., gas or steam turbine) is a power contributing to accelerate the machine. Small magnitude torques from frictional forces or auxiliary damper windings can also contribute. However, the fundamental electromechanical behavior of the synchronous machine connected to a transmission network can be simply understood as pictured in Figure 2.3: the machine accelerates or decelerates based on the difference between electrical power drawn by the network and applied mechanical shaft power; it operates at its steady state speed when these two powers are equal. Although perhaps obvious, it is worthwhile to stress that the generator does not independently determine its electrical power output. Rather, as a circuit element within the larger electrical network, the voltage/current solution at the generator terminals (and hence its electrical power) is determined by coupling of the generator’s constitutive relations with the boundary conditions imposed by connection to the transmission network. It is in this network coupling that a synchronous power grid gains much of its complexity as a control system, with the potential for dynamic response characteristics that can span much of a continent.

\(^4\) An observant reader will note that the constant speed/constant frequency approximation is used only selectively. Our objective is to write differential equations describing the time variation of frequency; so frequency is treated as a constant only in approximating the power-to-torque relation.
With each generator behaving according to an acceleration equation as pictured in Figure 2.3, the coupling effects due to the transmission network clearly act through the electric power output term, $P_E$. The vast majority of elements that make up the electrical components of the grid (i.e., transmission lines and transformers) are passive, with linear voltage-to-current relations. Hence, for a fixed network topology, and viewed from the nodes at which generators are attached, the relation of bus voltages to current drawn by the network is determined by a constant admittance matrix. However, adding to the interesting elements of grid control is the fact that the topology of the network is not wholly fixed and can be selectively changed by switching actions, as a class of discrete control actions. Typical in this class of discrete control actions is the switching in or out of shunt capacitors or relatively small step changes in the turns ratios of transformers. Given that the network must operate with voltages and current near to the desired 60 Hz or 50 Hz, the voltages and currents of interest are well-described as phasors with slowly varying magnitude and phase.\(^5\) The one-period average power associated with the nearly sinusoidal (voltage × current) product can then be described by sinusoidal (quasi–) steady state phasor analysis techniques, a standard tool of linear circuit analysis. Very importantly for our purpose here, it follows that the power absorbed by the network from a generator bus is a nonlinear function of the phase angle associated with the bus voltage phasor, and of the phase angles of other connected buses in the network. Moreover, the time rate of change of that bus voltage phase angle is, by definition, equal to the deviation in electrical frequency of the generator (i.e., deviation from the 50 Hz or 60 Hz synchronous reference). The result is that associated with each generator are two components for state equations governing its frequency and active power behavior, with network coupling between these sets dictated by the nonlinear power flow equations. In particular, one has this equation:

$$\frac{d\delta_i}{dt} = -M^{-1}i \ast P_{E,i}(\delta) + M^{-1}i \ast P_{M,i}$$

\(^5\) More precisely, one can consider this a Fourier-based, mixed-time-frequency representation in which the complex Fourier coefficient associated with the 60 Hz fundamental term of interest is band limited. In a polar representation of the complex Fourier coefficient, common approximations often further assume that the magnitude is approximately constant, and known, focusing then exclusively on time behavior of the angle.
\( \frac{d\delta_i}{dt} = \omega_i \)

where

- \( \omega_i \) = frequency deviation of machine at bus \( i \)
- \( \delta_i \) = phase angle of terminal voltage of the \( i^{th} \) machine
- \( \delta = n \)-dimensional vector of phase angles of network bus voltages
- \( M_i \) = normalized inertia of the \( i^{th} \) machine
- \( P_{E,i}(\delta) \) = electrical power delivered to network at bus \( i \)
- \( P_{M,i} \) = mechanical input power at generator shaft (from associated prime mover)

These state equations are approximations, in part because they choose a very simplified representation of effects related to control of the rotor winding magnetic field strength, which most strongly influences reactive power and magnitude of the voltage phasor. In particular, the previous representation assumes that a separate exciter control system, not explicitly modeled, functions perfectly to hold voltage magnitude to a fixed constant. However, by neglecting voltage magnitude and reactive power control, the previous equations are useful in capturing key aspects of active power and frequency behavior in the electric power grid. First, they highlight the role of mechanical powers from generators’ prime movers, \( P_{M,i} \), as a dominant class of controllable inputs to the system. Second, in the \( P_{E,i}(\delta) \) term, they illustrate the role of nonlinear network coupling. However, it is necessary to supplement these generator state equations in order to capture the effect of independent consumer demand, which in a control systems context plays the role of an exogenous disturbance input against which the system must regulate. In particular, these state equations are supplemented by constraints representing power balance at additional buses that are points of connection for load (e.g., substations). Depending on the modeling detail chosen to describe aggregate load behavior, the associated representation might be static, leading to algebraic constraints, or dynamic, yielding additional state equations. The simple static representation is often used and is illustrated here. For each load bus, active power balance simply requires that:

\[
0 = P_{D,k} - P_{E,k}(\delta)
\]

where

- \( P_{D,k} \) = active power load demand at bus \( k \)
- \( P_{E,k}(\delta) \) = electrical power delivered by network to bus \( k \)

With this formulation, one has a differential algebraic equation (DAE) model. For a network composed of \( n \) buses, \( m \) of which have generators attached \((m < n)\), one has \( m \) frequency variables and \( n \) phase angle variables,\(^6\) governed by \( 2m \) first-order differential equations, and \( n - m \) algebraic constraints [4].

\(^6\) Although not necessary for the development here, note that because power flow behavior depends only on differences of phase angles, common practice selects a bus as angle reference, and re-expresses all angles as differences relative to that reference. The reference angle can then be deleted from the set of variables.
With regard to $P_{D,k}$, the active load demand at bus $k$, in present day practice for most classes of customers, there is an “obligation to serve.” Hence, as noted previously, $P_{D,k}$ can be viewed as a stochastic, time-varying disturbance input that the system must regulate against. However, the situation is somewhat less challenging than this statement might suggest. Load demand at a bus typically aggregates a large number of individual pieces of equipment and/or customers. As a result, its average behavior is often very predictable, and relatively slowly varying (as compared to the timescale of dynamics of interest here). Thus, it is reasonable to treat $P_{D,k}$ as a sum of a fixed, predicted component, and a much smaller, zero-mean, stochastically varying component representing prediction error. The slow timescale set point selection for generators is optimized based on this load prediction; hence, it is only the much smaller load prediction error that fast timescale control must regulate against. Among the evolving challenges facing the grid, one notes that renewable generation sources such as wind and solar have impact equivalent to a negative load (assuming they are operated to maximally harvest weather-dependent available energy). While improving, today’s tools for predicting power output of wind and solar resources yield much larger stochastic error terms than those typical in load prediction, adding considerably to the control challenge of regulating against this new class of stochastic disturbance input.

A conceptual picture of the role of generator dynamics, load demand, and the coupling transmission network is illustrated in Figure 2.4.

**Figure 2.4 – Conceptual diagram: Nonlinear network coupling of coupling load demand to generator dynamics**
2.4.1 The role of the network and the nonlinear power flow

With the conceptual picture summarized in Figure 2.4 established, further attention can be directed to the nature of the coupling through nonlinear power flow terms, denoted as $P_E(\delta)$. Full detail on the power flow equations is beyond the scope of this brief chapter, but a number of features that affect dynamic behavior in the neighborhood of equilibrium are relevant. Considering local behavior, we note that the Jacobian $\partial P_E/\partial \delta$ has a structure that is well-approximated by a weighted Laplacian matrix, associated with the underlying graph of the transmission network. This situation gives rise to interesting qualitative features that affect control. For example, the connection weights for the Laplacian associated with $\partial P_E/\partial \delta$ decrease as the system operating point is more heavily loaded. In a rough mechanical analogy, the network performs like coupling springs, and the generators like mechanical masses, giving rise to a high dimensional spring-mass system. Important to the stability of the power grid is the recognition that the springs in this analogy exhibit a nonlinear force-to-displacement relation. As the power network is more heavily loaded at its equilibrium, the coupling “springs” become weaker, and the system becomes more prone to undesirable low frequency oscillations of generator frequencies and power flows. Moreover, the eigenstructure of Laplacian matrices also gives insight into the physical phenomena of coherency, in which low-frequency oscillatory modes often display an associated eigenvector (mode shape) in which groups of generators on one side of a heavily loaded cutset of network lines all swing together against a similarly coherent group for generators on the other side of the cutset. This oscillatory behavior predicted from the linearized DAE model is realized in the physical power grid by what are called interarea modes, and these can display associated swings of power between generators that might be hundreds of kilometers apart. To connect with the earlier description of control challenges in the grid, among the stability constraints imposed will include a requirement that these interarea modes are sufficiently well-damped. Given the nature of the nonlinear power flow equations, stability enhancement through control can have tremendous economic impact. By allowing adequate stability margins for heavily loaded operating points, one can more fully use the transfer capability of the grid. Conceptually, this capability enlarges the feasible region over which optimization is performed to select the generators’ MW set points; in practical terms, it often enables transfer of power from much more economic but distant generation sources.

2.4.2 Generator governor action as primary control

With an understanding of the underlying grid dynamics as outlined previously, some of the typical present day practices in grid control can be described. For an independent generator participating in a competitive power market, its most basic function is a regulating feedback loop seeking to hold power output to a specified value. Each time the generator receives an updated market command for a desired MW output, this update is simply a new set point to the feedback control system. This feedback measures terminal electrical power delivered and correspondingly adjusts the mechanical shaft power input (typically through valves controlling gas, or steam, or water flow delivered to a turbine). This basic control capability is common to almost all traditional generators; additional control functions can optionally be added. Typically, a significant percentage (but not all) of generators in a region will also provide governor droop control. As the nomenclature suggests, governor control is simply a feedback loop that measures the individual generator’s rotational speed/frequency as output, and modifies prime mover mechanical power in response. Experience in the early history of regional interconnection of generators confirmed that such multiple local feedback loops could not be practically implemented with each having integral gains, because small
errors in speed/frequency set points between different generators naturally give rise to marginally stable hunting oscillations in the interconnected system. Hence, current practice typically uses only the simplest possible proportional feedback for governor action. In power systems practice, proportional gain is characterized by the so-called droop constant, expressed as a percent value. The droop describes proportional feedback gain in terms of the percentage deviation in measured frequency that yields a commanded change in power equal to the MW rating of the generator, with typical droop values being on the order of a few percent.

The active/power frequency control functions described previously are in the category typically classified as primary generator control and operate on a relatively fast timescale of seconds. Within our model, the key exogenous disturbance driving the system is that of load demand, which continuously changes on a commensurate timescale of seconds, and is never perfectly balanced by the MW set points resulting from periodic market updates. Yet, because the previously described governor droop control is a purely proportional feedback, it inevitably suffers from steady-state error and cannot be expected to regulate system frequency precisely back to the desired 50 Hz or 60 Hz.

2.4.3 Automatic generation control as wide-area coordination

To address the steady-state error inherent in simple, local governor control, typical practice in power system operations applies another level of control action on a timescale slower than that of primary control, but more frequent than the 5-minute (or longer) period of market set point updates; this level is the so-called secondary control. As described earlier, the error signal measurement of interest is constructed over a regional footprint; in North America, management of secondary control is the responsibility of balancing authorities under the authority of NERC. Over the control area of interest, the ACE signal is constructed as a weighted sum of an area’s representative frequency error, and deviations from scheduled values for power flows on a set of monitored transmission tie lines. These tie lines are often key transmission corridors on the boundary of the region. The ACE signal is constructed in a centralized fashion by the balancing authority, which sends out ACE-based MW set point modifications to the participating generators in the region. To the non–utility specialist, the term can seem deceptively generic, but generators that receive and respond to this class of ACE-based control signal are said to be participating in automatic generation control (AGC). Exact practice varies, but common implementations might require generators participating in AGC to have a dedicated, highly reliable communication link to the balancing authority, with ACE-based MW set point updates being communicated at intervals on the order of once every 4 seconds. For such generators, these updates constitute incremental corrections to the megawatt output level determined by much slower periodic market updates. The contractual arrangements and financial reward mechanisms provided to generators for participating in these added control functions are beyond the scope of this chapter. However, looking ahead to the future of Smart Grid technologies, it is very important to note that it is exactly these aspects of present-day control practice that one might wish to open to a wider class of new technologies and new participants. Careful characterization of the underlying control objective must play an important role in setting policies, reward mechanisms, and communications/control security requirements for new players that might contribute to these grid control needs.
2.5 Reactive power and voltage magnitude control

The framework of active power frequency regulation outlined previously represents one of the major components of wide-area control in the electric power grid. However, a range of other control functions are currently exercised, both continuous and discrete, several of which might take on more importance in the future evolution of the Smart Grid. No less important than active power control/frequency regulation is the control of reactive power for regulation of voltage magnitudes [10]. An important qualitative feature of power flow in a synchronous grid can be observed when power balance equations are written in sufficient detail to represent reactive power balance at buses and its dependence on voltage magnitude variations. (Recall that the previous simplified presentation approximated voltage magnitudes to be fixed constants.) If reactive power drawn or injected into the network at a bus is treated as a control input, the coupling of this input to the response of voltage magnitude at that bus is quite strong, while coupling to voltage phase angles is typically weak. Moreover, the impact of reactive power injection at a specific bus on voltage magnitudes at neighboring buses drops off quickly away from the point of injection. Hence, the problem of regulating voltage tends to be a more localized problem, with a controllable reactive source at a given bus being responsible for regulating voltage magnitude to a desired set point at that bus or at a nearby neighboring group of buses. Synchronous generators are one of the classes of equipment that can effectuate voltage regulation, with their reactive power output being varied by the strength of the magnetic field in their rotor winding. The nominal direct current (DC) voltage applied to the rotor winding of the generator is the physical control input signal, and the generator’s AC terminal bus voltage magnitude is typically the output quantity to be regulated. The overall system that measures terminal voltage and varies the field voltage to regulate terminal voltage magnitude to set point is called the generator’s excitation system. In simplified analyses, this system can be treated as entirely decoupled from active power and frequency behavior. However, a more accurate model must recognize that there is coupling, and indeed, this coupling of voltage magnitude behavior to frequency and angle can be exploited to design stability-enhancing supplementary controls. Although their use is not widespread, some generators might have an auxiliary feedback loop that modulates field voltage in response to measured frequency, with the objective of improving the damping of the oscillatory power/frequency modes discussed earlier. These excitation-based feedback controls are generally called power system stabilizers.

Other classes of equipment that might contribute to reactive power control and voltage regulation include continuously acting, power-electronic-based technologies such as static VAR compensators (SVC), or more traditional discrete devices such as switched capacitor banks. Another class of discrete switching controls can help regulate voltage magnitude by a somewhat different mechanism, by varying the turn ratios of transformers. In their simplest form, these tap changing transformers might sit along a radial connection between the higher voltage transmission system and the lower voltage load connection. By switching between taps of the transformer, the voltage step-down ratio can be varied over several percent about its nominal value, thereby allowing the voltage at the customer side to be regulated towards its desired value. Through these various classes of voltage regulating controls, voltage magnitudes are typically held to a range of roughly ± 5% about their nominal values, partially justifying the assumptions of the simplified model employed earlier, in which voltage magnitudes were treated as fixed.

Although some aspects of the voltage control problem can be viewed as more localized, and therefore perhaps less challenging than active power/frequency control, this distinction is far from absolute. As new classes of customer equipment become more widespread, the characteristics of load response can change in ways that make voltage stability problems more critical. Power electronic regulated power
supplies and variable-speed motor drives offer examples of equipment that provide desirable characteristics from the end-use perspective, but they can be detrimental to grid voltage stability characteristics if not designed to consider larger-scale system needs. In some regions of the U.S., the characteristics of modern, high-efficiency air conditioning units have challenged voltage stability, contributing to an undesirable phenomenon called fault-induced delayed voltage recovery (FIDVR). Although the details of these wide-ranging phenomena are beyond the scope of this short tutorial exposition, they are highlighted to alert the reader to the scope of control challenges that exist in the power grid. Advances in Smart Grid technologies hold great promise to help address many of these, but the complexity of the power grid also cautions that thorough analysis is necessary to avoid unintended consequences and undesirable coupling between controllers designed to address local objectives. As in the example of modern air conditioners, it is important that control design for new technologies consider both the end user objective (e.g., efficiency) and well as the potential for wider system impacts (e.g., FIDVR).

2.6 Communication, measurement and computational architectures supporting present day grid control

One of the key contributions anticipated in the advance of Smart Grid technologies is that of enhanced high bandwidth, wide-area communication, with much of this communication infrastructure serving improved control functions. Therefore, to understand the opportunities for new technologies to improve on current practice, it is worthwhile to examine the communication structure that supports present day control in the grid. A useful technical overview of grid communication practices, composed from the viewpoint of a non-power systems specialist, can be found in one of the online references [7].

The power system currently uses several media for its protection, control, and information-sharing functions. The most common ones include: power line carrier (PLC), microwave, fiber-optic, pilot wire and wireless. PLC operates by transmitting radio frequency signals between 10 kHz to 490 kHz over the transmission lines. Such carrier signals can employ a (communication) transmit power output on the order 150 watts over distances of up to 150 miles, depending on the continuity of the line and deployment of repeaters around breakers and transformers. Typically, PLC carries one channel having 4 kHz bandwidth. The frequency range is limited by government regulations. The PLC is the most common communication media used in the U.S. for communicating signals that help inform the action of protective relaying, which serve as the advanced “fuses” on the network to protect equipment from fault-induced overloads. Historically, the design of such protection equipment was carried out largely separate from that of the continuously acting controls described previously, but clearly, from a conceptual standpoint, protective relays constitute a class of discrete event controls. One of the promising avenues for future grid enhancement will lie in more strongly coordinating the design of protection with other grid control actions. The communication schemes that allow such discrete acting controls and protective relays to be more aware of system-wide conditions will play an important role.

Microwave communications have historically been another widely used class of communication in grid operations. Such microwave links operate in the 150 MHz to 20 GHz range and offer significant bandwidth for many communication channels that carry a range of grid operational and measurement data. However, microwave communications carry a number of disadvantages: 1) the transmission length is limited to a line of sight path between antennas, 2) they are subject to atmospheric
attenuation and distortion, and 3) typical latency is approximately 100 milliseconds between two adjacent antennas.

Dedicated fiber-optic communication links, including optical ground wire (OPGW) equipment, are today considered the most reliable and secure media of communication in grid operations, and are often preferred in support of high-impact, wide-area control schemes. A single fiber cable can carry up to 8000 channels at typical data rates of interest in grid applications, and has the advantages of very low latency, immunity to switching transients, and no interference from other electric systems, even in the high field strength that exists along bulk transmission lines (operating at 345 kV, 500 kV, or 765 kV in the U.S.). The only disadvantages are the cost of the cable system and the cost of construction.

Other communication mechanisms used in bulk-transmission utility operations today include wired telephone, either owned by utility companies or leased from telecommunication companies, as well as variety of wireless schemes, particularly in local networks such as substations. Clearly, security is a major concern on any communication link that can affect physical grid operations, and this is particularly true in wireless or other networks that might provide direct or indirect links to public networks. The growing recognition of cyber-physical security needs is reflected in current practice. In the U.S., NERC, with regulatory backing from FERC under its Critical Infrastructure Protection standards of Order No. 706, enforces a range of binding regulations governing cyber security practice, many of which relate to limiting communication vulnerabilities. These issues are certain to take on even greater importance in the future, as the Smart Grid comes to rely heavily on both greater communication and on greater numbers of actors and more distributed actors contributing to grid control.

Building on these underlying communication layers, a number of higher level critical systems form the architecture of present day grid control operations. The key IEEE standards document [3] relating to grid measurement and control systems contains very useful tutorial background material on such higher-level elements of grid control. These elements include the following topics:

Control center energy management system (EMS): An energy management system (EMS) is a general term used to describe a wide ranging suite of software and hardware that supports a regional control center in managing the production, purchasing, transmission, distribution, and sale of electrical energy in the power system at a minimal cost with respect to safety and reliability. Management of the real-time operation of an electric power system, whether in a wholesale market environment coordinated by an ISO or in a vertically integrated utility environment, is a complex task that requires interaction of human operators, computer systems, communications networks, and real-time data-gathering devices in power plants and substations. Taking the ISO example, a typical ISO control center is a physical site (with a redundant backup site) in which human operators oversee computers running large software suites, display devices, communication channels, and remote terminal units (RTU) that are connected to control actuators and transducers in power plants and substations. The main tasks that a control center performs are related to generator control and scheduling, network analysis and component switching (e.g., operation of switched capacitor banks), and operator training. The operation of generation previously described requires that the control center monitor thousands of telemetered values, estimate the electrical state of the network, and provide software supported decision tools to help the operator select the best strategy to handle potential outages, overloads, or operating-limit violation on equipment. Hence, it is common for control centers to have real-time two-way communication links between substations, power plants, ISOs, and other control centers.
Supervisory control and data acquisition (SCADA) system: SCADA has historically been used by the power system community as an umbrella term to describe the wide range of physical measurement and communication systems supporting operator control of remote (or local) equipment, whether the physical media be microwave link, fiber optics, or wire line, and whether the control operation is opening or closing a network circuit breaker or commanding a set point change to a generator. A SCADA system provides three critical functions in the operation of an electric power system: data acquisition, supervisory control, and alarm display. It consists of one or more computers with appropriate applications software connected by a communications system to a number of RTUs placed at various locations to collect data, perform intelligent control of electrical system devices, and report results back to an EMS. The term SCADA is often used also to describe similar applications in natural gas pipeline transmission and distribution applications. In anticipating the future of grid technology and operations, it is worthwhile to consider the strong possibility that Smart Grid technologies will seek stronger coordination and co-optimization between the power grid infrastructure and other energy infrastructures such as gas pipelines.

Phasor measurement units (PMU): Notable among recent trends in present-day grid measurement technology has been the enhancement and expansion of the wide-area measurement system (WAMS), using satellite time stamping to coordinate data coming from sensors distributed over a large regional network. To date, the main function supported by the WAMS has been power system quasi-steady state estimation, though opportunities for more advanced estimation of dynamic state behavior and system stability properties hold great promise. Synchronized PMUs provide measurements of the voltage and current magnitudes and phase angles, precisely time synchronized across large geographic distances. These measurements, along with simple binary reporting of circuit breaker status, are extremely valuable for estimating real-time power flows on transmission lines, and for confirming system topology. These are key to informing secondary control and for the computation of locational marginal prices in operation of wholesale power markets. Phasor measurement units are being deployed aggressively in the U.S. and globally. In 2009, there were about 200 PMUs in operation in the U.S.; by the end of 2013, this figure will rise to over 1000 installed PMUs. Each PMU can provide 10 to 12 separate measurements, including voltages, currents, and frequencies, reported at a rate of 30 or 60 samples per second. This new class of high bandwidth measurement offers tremendous improvement over the 2-second to 4-second period unsynchronized reporting of the older SCADA measurement technologies that preceded it.

Remote terminal unit (RTU): RTUs are special-purpose microprocessor-based computers that contain analog-to-digital converters (ADC) and digital-to-analog converters (DAC), digital inputs for status, and digital output for control. There are transmission substation RTUs and distribution automation (DA) RTUs. Transmission substation RTUs are deployed at substation and generation facilities, where a large number of status and control points are required. RTUs can be configured and interrogated using telecommunication technologies. They can have hundreds of real-time communication links with other substations, EMSs, and power plants.

Programmable logic controller (PLC): PLCs have been used extensively in manufacturing and process industries for many years and are now being used to implement relay and control systems in

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7 The reader will note the importance of precise time synchronization when measuring relative phase of sinusoidal voltages, between buses that could be many hundreds of miles apart. Reliably and precisely obtaining time synchronization between measurements separated by long distances was historically quite costly; today, very low-cost GPS chip sets easily provide this time synchronization.
substations. PLCs have extended input/output (I/O) systems similar to transmission substation RTUs. The control outputs can be controlled by software in the PLC and by remote commands from a SCADA system. The PLC user can make changes to the control logic without making any major hardware or software changes. In some applications, PLCs with RTU-reporting capability might have advantages over conventional RTUs. PLCs are also used in many power plant and refinery applications. They were originally designed for use in discrete applications like coal handling. They are now being used in continuous control applications such as feedwater control. PLCs can have many real-time communication links inside and outside of substations or plants.

**Protective relays:** Protective relays are designed to respond to system faults and short circuits. When faults occur, the relays must signal the appropriate circuit breakers to trip and isolate the faulted equipment. Distribution system relaying must be coordinated with fuses and reclosures for faults while ignoring cold-load pickup, capacitor-bank switching, and transformer energization. Transmission-line relaying must locate and isolate a fault with sufficient speed to preserve stability, reduce fault damage, and minimize the impact on the power system. Certain types of “smart” protective relays can be configured and interrogated using telecommunication technologies.

**Automated metering:** Automated metering is designed to upload residential and/or commercial gas and/or electric meter data. These data can then be automatically downloaded to a PC or other device and transmitted to a central collection point. With this technology, real-time communication links exist outside of the utility infrastructure.

**Plant distributed control systems (DCS):** DCSs are plant-wide control systems that are used for power plant automation and control. These systems typically operate within the footprint of a single generating station, or a geographically co-located group of stations, and hence often represent just a single node of bus within the larger grid. Nonetheless, the complexity of processes within such a single power plant location can be very large, with I/O counts that can be greater than 20,000 data points. Often, the DCS is used as the plant data highway for communication to and from intelligent field devices, other control systems (such as PLCs), RTUs, and even the corporate data network for enterprise resource planning (ERP) applications. Traditionally, the DCS used a proprietary operating system, but in recent years they have moved to open systems. DCS technology has long been developed with reliability, operating efficiency, and user configurability as key drivers. In recent years, the need for cyber security has become a critical added criterion. Although perhaps common to many process industries, the geographically distributed nature of the power grid makes trade-offs between security and operational/staffing efficiency particularly apparent. For example, technologies for remote access to facilities (such as geographically remote hydroelectric generating plants) to view and potentially reconfigure the operating parameters are quite attractive from the standpoint of operational efficiency. However, these must be deployed with very strong protection against cyber attacks that might subvert control of such power plants, potentially affecting the grid far beyond the confines of the one compromised facility.

2.7 **Interdependencies with other cyber and digital infrastructures**

As noted previously, the technological and social trends underlying the Smart Grid suggest tighter integration between power grid operation and control and that of other infrastructures. However, significant couplings across infrastructures exist today. Electric power utilities typically own and operate at least parts of their own telecommunication systems, which often consist of backbone fiber
optic or microwave connecting major substations, with spurs to smaller sites. The energy industry has historically operated closed, tightly controlled networks. Deregulation and the resulting commercial influences have placed new information-sharing demands on the energy industry. Traditional external entities like suppliers, consumers, regulators, and even competitors now must have access to segments of the network. The definition of the network must be expanded to include the external wide-area network connections for these external entities. This expansion greatly increases the security risk to other functional segments of the internal network that must be protected from external connections. This is true whether a private network or the Internet is used to support the external wide-area network.

The external entities already have connections to the Internet, and as such the Internet can provide the backbone for the external wide-area network. The aforementioned cyber security concerns sometimes are judged sufficient that creation of a fully separate private network is judged worthwhile. However, duplicating this backbone to create a private network requires not only large startup costs but also ongoing maintenance costs and potentially higher individual transaction costs than using the Internet, suggesting that more sophisticated means of security that can safely allow use of public networks is an attractive area for development.

Increased use of electronic automation raises issues regarding adequacy of operational security:

- Reduced personnel at remote sites makes them more vulnerable to hostile threats
- Interconnection of automation and control systems with public data networks makes them accessible to individuals and organizations—from any worldwide location using an inexpensive computer and a modem
- Use of networked electronic systems for metering, scheduling, trading, or e-commerce imposes numerous financial risks

Some utilities have diversified their businesses by investing in telecommunications and creating innovative communication networks that cope with industry trends toward distributed resources, two-way customer communications, and business expansion, as well as addressing the measurement of complex and data-intensive energy systems by wide-area monitoring and control. Utility telecommunications include several media and diversified communication networks, which in part provide redundancy. These range from dedicated fiber-optic cables, digital and analog microwave, and very-small-aperture terminal (VSAT) satellites to PLC technology, as well as the use of multiple address radios, spread-spectrum radios, trunk mobile radios, and cellular digital packet data.

Security of these cyber and communication networks is fundamental to the reliable operation of the grid. As power systems rely more heavily on computerized communications and control, system security increasingly depends on protecting the integrity of the associated information systems. Part of the problem today is that existing control systems, which were originally designed for use with proprietary, standalone communication networks, were later connected to the Internet (because of its productivity advantages and lower costs) but without adding the technology needed to make them secure. As noted previously, cyber security in such an environment is already a rapidly growing area for standards and regulation as set by NERC and FERC, and for Smart Grid research. Optimally managing the potential trade-offs between robust security and high performance in normal, uncompromised operations will likely be a particular area of interest in advanced communication/control design for the Smart Grid.
2.8 Summary

Successful operation of today’s power grid rests heavily on a huge array of control systems, organized in a hierarchy according to both geographic scale of impact and timescale of the phenomena to be controlled. This chapter provided a brief overview of how many of these pieces fit together, form the governor feedback loop operating on an individual generator, to the market coordination of hundreds of generators across the large geographic footprint of a modern ISO. In considering these existing practices, and the characteristics of new technologies affecting generation, consumption, and storage of electric power, one can project many of the future control system challenges inherent in the Smart Grid. To gain the improved efficiencies that could come from responsive load (i.e., no longer forcing loads to behave as inelastic consumers), and to exploit the reduced environmental impact enabled by renewable generation, it will be imperative to open the power grid to a much larger number of contributors to control. Many of these new classes of contributors to the grid control will have very different characteristics relative to those of large synchronous generators, which have long been the dominant hardware in grid control. Abstracting from a control system perspective, one will have a distributed control problem, with both larger numbers of individual actuators contributing, and with these actuators themselves having a much wider variety of dynamic characteristics. Facilitating the effective use of these many new control contributors will be the three supporting technologies of improved communications, measurement, and computation. The subsequent chapters will explore future grid control scenarios and opportunities for enhanced efficiency and reduced environmental impact in electric energy systems that can be enabled by advances in control.

2.9 Citations


3.1 Introduction

Chapter 2 described the areas of the grid in which control currently plays a significant role, including power balance, frequency regulation, and reactive power control. Global movements toward Smart Grid development are significantly expanding the role of control in the grid; these movements are occurring across a wide socio-economic technological canvas, and taking the shape of several multifaceted global drivers stemming from various sources. This chapter focuses on the major drivers for the development of the Smart Grid.

The first of these drivers is environmental stewardship. It is impossible to anticipate whether an oil peak will come (because new discoveries have occurred repeatedly), to what extent shale gas will prove viable, or whether and when carbon capture and storage (CCS) will be commercialized. However, all of these firmly underscore the need for green energy and decarbonization.

Although decarbonization is a major trend in countries such as the U.S., as well as the E.U., developing countries face a different challenge: ensuring reliable and affordable power in the face of an explosive growth in demand. This challenge, together with aging infrastructures, represents the second major driver.

The third driver that necessitates large changes in the grid infrastructure is the possibility of significant increase in electrified transportation. Uncertainties in the fossil fuel scene are spurring large advances in electric vehicles, both for personal and for mass transit. The transportation sector in the U.S., for example, consumes two-thirds of the total oil used. Hence, a move away from hydrocarbon-based propulsion and towards electric ones is yet another major driver.
The fourth driver is the emergence of an empowered consumer, made possible through a combination of technological, social, and behavioral changes, all of which will allow loads to be responsive to the grid’s needs. In several places across the globe, such demand response might be the only available asset to cope with unprecedented growth in the demand.

The final driver towards development of the Smart Grid is a globally pervasive set of changes in the regulatory paradigms and market designs in the energy domain. The previous five drivers are discussed in Section 3.2 through Section 3.6.

The ammunition for fighting the challenges that these drivers precipitate comes from technology, standards, and policy. In terms of technology, the Smart Grid will be driven by a cyber infrastructure in which where power flow is enabled through wide-area sensing, advanced communications, control, and distributed actuation. As will be expanded in Chapter 4 and Chapter 5, this cyber infrastructure is very much control-based and needs to be designed so as to not only allow efficient using the grid’s high-capital-cost physical infrastructure but also to achieve better performance, lower cost, and reduced environmental impact.

3.2 Driver 1: Decarbonization

Worldwide, the main driver for development of the Smart Grid is decarbonization. The European Union, for instance, has reinforced its commitment, by 2050, to reduce the greenhouse gas emissions of the power sector to 80% to 95% of the levels that existed in the 1990s [7]. Instead of resource scarcity or technology limitations, society’s future energy choices will likely be dominated by environmental constraints and compliance with local, national, and global initiatives directly related to these issues. Over the next 25 years, substantial progress will almost certainly be achieved in improving our understanding of key environmental issues, and in using electricity innovations to resolve them.

The global decarbonization of our energy system has been steadily advancing for the last 150 years, facilitated to an ever-greater degree by electricity. In the early part of the nineteenth century, wood yielded to coal, and, subsequently, in the twentieth century and twenty-first century, to oil, natural gas, renewables, and nuclear power. This path puts us on a trajectory toward a clean, electricity- and hydrogen-based energy economy by the end of the twenty-first century. As we electrify, coal and oil can drop from approximately 50% of the global energy mix today to less than 5% over the next century. Taking into account this longer perspective, the issue is not whether the carbon emissions of a few nations in 2010 return to levels of the 1990s. Rather, our goal should be to reduce global carbon emissions to 1900 levels by 2100.

3.2.1 Renewable power production

When commercial interest in renewable energy resources peaked after the oil crisis of the 1970s, the results included some interesting technology developments but generally poor financial returns for early investors. The decline of oil and gas prices during the 1980s made it even more difficult for emerging renewable energy technologies to compete in anything but niche applications. In 2012, now that concerns over global climate change and energy security have grown, interest in renewables is on the upswing once more. Today, investments in renewable energy are more firmly market-based and are supported by more solid technological and regulatory foundations (including Renewable Portfolio Standards adopted by many states) [4]. Several renewable resources have become economically
appealing in their own right, and the groundswell to adopt constraints on carbon emissions might continue to improve their competitive position with respect to fossil fuels.

Renewable energy resources such as solar and wind energy have a number of favorable aspects: they are clean, their supply is not depleted over time, and they are—at least from a fuel standpoint—free. In response to the high global demand resulting from government mandates for renewable energy, installation of wind and solar photovoltaic generation is proceeding at a rapid pace worldwide, growing at 20% to 30% per year. Because the demand for wind turbine equipment and services exceeds the available supply and the supply of pure silicon for solar photovoltaic (PV) cells is limited, wind and solar PV have experienced a 10% to 30% increase in installed costs since 2004. However, the wind and solar PV industries are expanding manufacturing capabilities and continue to improve the performance of their products, which will ultimately lead to further reductions of both the installed cost and the cost of the electricity they produce.

Integrating large-scale renewable power—particularly wind and solar energy—into the electric power infrastructure presents significant challenges. At the heart of this challenge lies the inherent variability (often referred to as intermittency) of wind and solar, which differentiates these two resources from other renewable resources. Two recent publicized incidents illustrate some of the challenges associated with variable resources. The first incident, an example of the potential short-term operational impacts, occurred in Texas, U.S., on February 26, 2008. At that time, the Electric Reliability Council of Texas (ERCOT) experienced a large underfrequency event as a result of wind generation output unexpectedly dropping 1400 MW over approximately 3 hours during the evening peak load ramp [4]. The second incident, an example of potential long-term supply adequacy impacts, occurred in California, U.S., during a heat wave in the summer of 2006. During this time, the California ISO experienced significant system operation problems due to supply deficiencies of 2700 MW of installed wind generation capacity operating at capacity factors between 2% and 10% [4].

### 3.2.2 Growing carbon footprint

Despite the economic downturn of the early 2010s, there is a reasonable consensus that additional electric power generation will be required in the decades ahead to supplement aggressive efforts to increase energy efficiency and manage demand. Ultimately, the choice between available generation technologies will depend on a variety of factors, including resource locations, local preferences, and especially the comparative costs of electricity produced. Higher market prices for carbon credits, for example, will tend to favor nuclear and renewable resources over coal and natural gas.

The United States and other energy-intensive economies around the world must keep all of its major energy options open to meet the economic and environmental uncertainties of the future. For electricity, this means building and sustaining a robust portfolio of clean, affordable options, ensuring the continued use of coal, nuclear, gas, renewables, and end-use efficiency. Foreclosing any of these options in the first half of the twenty-first century could greatly impair efforts to achieve a sustainable energy future. Prudent investment decisions for plants that produce electricity for the next 30 to 50 years will be increasingly based on the assumption that carbon constraints are coming. The price that decision makers assume for the future cost of CO₂ emission (e.g., zero, as it is today, $30/tCO₂, $50/tCO₂, or more) will dramatically change the relative costs of the various supply options.

Advances in various types of power generation play an increasingly important role in a carbon-constrained future. Because coal is such an important resource in so many major economies, the development and deployment of affordable, efficient new coal technologies that produce less CO₂ are
key to meeting targets for reducing CO₂ without risking global economic instability. Two promising technologies in this regard are those that are based on direct combustion such as ultra-supercritical (USC) plant designs and integrated gasification combined cycle (IGCC) systems, which combine high efficiency, low emissions, and low water usage of combustion turbines with the ability to run on syngas, which can be coal-derived. Combustion turbines (CT) burning natural gas offer the lowest investment requirements of any new type of commercially available central station plant. They are very efficient (which reduces CO₂ emissions), have a small plant footprint, can be readily sited, and can be constructed in a much shorter period of time than other large-scale power generation options. Improvements in carbon capture and storage methods and their cost-effectiveness might also significantly alter the equation when it comes to coal. Finally, as the most widely deployed carbon-free technology, nuclear power could play an important role in stabilizing atmospheric CO₂ levels as well.

3.3 Driver 2: Reliability in the face of growing demand

3.3.1 Current status in the U.S.

Power outages and power quality disturbances cost the U.S. economy over $80 billion annually, and up to $188 billion per year. Transmission and distribution losses in the U.S. were about 5% in 1970, and grew to 9.5% in 2001, due to heavier usage and more frequent congestion. Regarding the former, beginning in 1995 the amortization/depreciation rate exceeded utility construction expenditures. Since that crossover point in 1995, utility construction expenditures have lagged behind asset depreciation. This lag has resulted in a mode of operation of the system that is analogous to harvesting crops more rapidly than planting replacement seeds. As a result of these diminished “shock absorbers,” the electric grid is becoming increasingly stressed, and whether the carrying capacity or safety margin will exist to support anticipated demand is in question.

In the U.S., many parts of the electric grid infrastructure are over 25 to 30 years old. For example, the key elements and principles of operation for power grids were established in the 1960s or 1970s, before the emergence of extensive computer and communication networks. Today, computer simulations support all of the planning and most of the operational control that goes into assuring the success of its primary function: to deliver bulk electric power from generation sources to load areas reliably and economically. In the past, the assurance of reliability has been the overwhelming goal in performing this function.

From a broader view, the North American electricity infrastructure is vulnerable to increasing stresses from several sources. One stress is caused by an imbalance between growth in demand for power and enhancement of the power delivery system to support this growth. From 1988 to 1998, the U.S.’s electricity demand rose by nearly 30%, but the capacity of its transmission network grew by only 15%. This disparity increased from 1999 to 2009: demand grew by approximately 20%, while planned transmission systems grew by less than 3.8%. Along with that imbalance, today’s power systems have several sources of stress:

- **Demand is outpacing infrastructure expansion and maintenance investments.** Generation and transmission capacity margins are shrinking and unable to meet peak conditions, particularly when multiple failures occur while electricity demand continues to grow.
• The transition to deregulation is creating new demands that are not being met. Because the electricity infrastructure is not being expanded or enhanced to meet the demands of wholesale competition in the industry, connectivity between consumers and markets is at a gridlock.

• Return on investment uncertainties is discouraging investments in infrastructure upgrades. Investing in new infrastructure technologies can meet these aforementioned demands. More specifically, according to a June 2003 report by the National Science Foundation, research and development (R&D) spending in the U.S. as a percent of net sales in 1999 was about 10% in the computer and electronic products industry and 12% in the communication equipment industry. Conversely, R&D investment by electric utilities was less than 0.5% during that time. In most other industries, R&D investment is also significantly greater than in the electric power industry.

• Concern about the national infrastructure’s security. A successful terrorist attempt to disrupt electricity supplies could have devastating effects on national security, the economy, and human life. Yet power systems have widely dispersed assets that can never be absolutely defended against a determined attack.

The current power infrastructure’s usage capacity remains the lowest among all national critical infrastructure systems—approximately 50% on average, which is exacerbated by two other trends over the past three decades: 1) increased pinch points in transfer capacities in major transmission corridors, and 2) increased frequency and costs of outages and power quality disruptions (see Figure 3.1).

Figure 3.1 – Capacity challenges/opportunities: This figure indicates that demand response is very much needed because on the average, less than 50% is used. However, sufficient generation capacity that is capable of meeting peak demand has been declining over the past 20 years. [11]
To assess impacts using actual electric power outage data for the U.S., we analyzed data from the U.S. DOE Energy Information Administration (EIA) and the North American Electric Reliability Corporation (NERC) [5]. In general, the EIA database contains more events, while the NERC database provides more information about the events, but both databases are extremely valuable sources of information and insight. Analyses of these data reveals that between 1991 and 2000, there were 76 outages of 100 MW or more in the second half of the decade, compared to 66 such occurrences in the first half of the decade (Figure 3.2).

Furthermore, there were 41% more outages affecting 50,000 or more consumers in the second half of the 1990s than in the first half (58 outages between 1996 and 2000, versus 41 outages between 1991 and 1995). In addition, between 1996 and 2000, outages affected 15% more consumers than they did between 1991 and 1995. (The average size per event was 409,854 customers affected in the second half of the decade versus 355,204 in the first half of the decade.) Similar results were determined for a multitude of additional statistics such as the kilowatt magnitude of the outage, average load lost, etc. These trends have persisted in this decade. NERC data show that between 2001 and 2005 there were 140 occurrences of over 100 MW dropped and 92 occurrences of 50,000 or more consumers affected [5].

According to the EIA database, each 5-year period was worse than the preceding one. Between 2000 and 2004, there were 156 outages of 100 MW or more; such outages increased to 264 between 2005 and 2009. The number of U.S. power outages affecting 50,000 or more consumers increased from 149 between 2000 and 2004, to 349 between 2005 and 2009, according to EIA (see Figure 3.3) [5].
In summary, the number of outages between 2000 and 2009 (adjusted for 0.9% annual increase in load and adjusted for change in reporting in 2003) is shown in Table 3.1.

**Table 3.1 – Power outages between 2000 and 2009**

<table>
<thead>
<tr>
<th></th>
<th>Occurrences of 100 MW or more</th>
<th>Occurrences of 50,000 or more consumers</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000–2004</td>
<td>152</td>
<td>130</td>
</tr>
<tr>
<td>2005–2009</td>
<td>248</td>
<td>272</td>
</tr>
</tbody>
</table>

There have been additional major electric power disturbances affecting over 1 million consumers in the U.S.:

- 2010 Southeastern U.S. (Hurricane Irene): 5 million affected
- 2011 Texas (forced outages due to cold weather): 1 million affected
- 2011 Southern California/Arizona (substation equipment failure): 5 million affected
- 2012 Mid-Atlantic U.S. (severe thunderstorms): 4 million affected
As noted in the comprehensive report [9], electricity service has been provided reliably for more than 100 years, and it is argued that grid conditions might not be that bad. However, a major study of reliability trends shows that power interruptions have increased at a steady rate of approximately 2% per year over a period of 10 years [6]. In the U.S., the grid averages 92 to 214 minutes of interrupted service, or blackouts, per customer per year (depending on which part of the country they live in). The outage data excludes interruptions caused by extreme events precipitated by fires or weather. Japan, by contrast, averages only four minutes of interrupted service per year per customer. The total number of outages and power quality disruptions cost the U.S. an average of over $100 billion per year, with a range of $80 billion to $188 billion. A better grid that accommodates the changing landscape of generation and growing demand might be called for and is perhaps within reach to meet the needs of pervasive digital society across the globe.

### 3.3.1.1 Current global conditions

From a more global perspective, electricity demand has been growing rapidly in many nations, while the generation, transmission, and distribution infrastructure expansion has not kept up with demand. This lag has contributed to several major outages around the world:

1. **Brazil**
   - 1999 (busbar short due to lightning): 99 million affected
   - 2007 Ispirito, Brazil (cyber attack): 3 million affected
   - 2009 Brazil and Paraguay (storms): 67 million affected
   - 2011 northeast Brazil: 53 million affected

2. **Japan**
   - 1987 Tokyo, Japan (demand increase): 2.8 million affected
   - 2004 Kyushu, Japan (typhoon): 1 million affected
   - 2005 Tokyo, Japan (crane hit transmission line): 1.4 million affected
   - 2011 northern Japan (earthquake/tsunami hit Fukushima): 30 million affected

3. **India**
   - 2001 (electric power outages): 200 million people affected
   - 2012 (electric power outages): 370 million affected in northern India, followed by 670 million affected in northern and eastern India

In relation to the recent massive power outage in India in 2012, it might be too early to say what the precise cause was. However, at its root, it is very likely to have to do with supply and demand, lack of real-time situational awareness and control, and weak monsoons severely compromising the country’s major source of power (hydroelectric generation). Regular localized outages and daily load shedding are common throughout India, as power grid controllers are forced to make cuts to keep the system in balance. As a result, many businesses, hospitals, and airports use generators to make up for the temporary shortfalls in available electricity. In a large city like Bangalore, 30 to 45 minutes of load shedding per day is common. Another part of India’s inability to keep up with demand is the massive losses experienced in the country’s transmission and distribution network as a result of illegal connections. In some Indian states, the power losses are as high as 50% because of theft. India also needs better control systems to be able to rapidly sense and change the resistance of its transmission lines—technology that has not been widely used in the country. India’s power issues are even more compelling when coupled with the fact that 40% of Indian residences have no electricity at all [17].
Fixing these problems will take large amounts of investment and a crackdown on power theft—two goals that are difficult to square with one another. As of 2012, India is still highly reliant on coal-fired generation, but because the quality of its domestic coal production is poor, the country relies heavily on imported coal. Consequently, India is trying to increase gas generation. Domestic and international investment would help, but that requires long-term commitments and policy reform.

3.4 Driver 3: Electrification of transportation

Fortunately, the future looks very bright for electricity’s role in transportation over the next 25 years. The transportation sector consumes about two-thirds of the oil used in the U.S. In the absence of viable alternatives to oil, world demand and tension over the fossil fuel will only continue to grow.

Over the next 25 years, electricity is expected to play an increasing role in transportation. Electric vehicles (EV) are nearly twice as energy efficient as internal combustion-powered vehicles, and are emission-free at the point of use. In addition, they provide fuel flexibility to reduce dependence on oil. India and China, for example, represent enormous, practical markets for EVs, in part because of deteriorating air quality in their rapidly expanding cities and their lack of petroleum infrastructure. The market for EVs will take decades to fully develop, but from a technical, marketing, and investment perspective, it is now underway because every major automobile manufacturer is active in the development of these vehicles. In time, electric vehicles could lead to mobile distributed power sources. Imagine cars that have thermal efficiencies greater than 60% with the performance characteristics of a sports car, which can also supply electricity to your home when you are not on the road. For dense traffic corridors, high-speed, magnetic levitation (maglev) trains offer an attractive alternative to increasingly congested airports. Imagine highly efficient maglev trains operating in vacuum tunnels and carrying 10,000 passengers per hour between cities up to 1200 miles apart in less than an hour. These trains could help to control urban growth, congestion, and wasted time.

The large increase of electrified transportation has obvious implications on the grid, which are addressed in the following sections.

3.4.1 Grid integrated with electric transportation: Motivating drivers

Next-generation rail and road vehicular transportation systems will increasingly depend on electricity supplied by the grid as the preferred energy source for propulsion. Systems of interest in this scenario include not only personal and commercial fleets of EVs, but electrically powered trains, both passenger and freight. Innovative, collaborative control strategies in the electrical network and transportation network can achieve many benefits compared to independent operation. Several simple examples illustrate the kinds of problems faced in resolving the frequently conflicting objectives of two groups: 1) power producers’ issues related to renewable intermittency compensation, carbon footprint, and efficiency of energy use, and 2) completion of the transportation sector’s core mission of moving goods and people. These examples include the following problem cases:

- In the rapidly growing city of Sao Paulo, Brazil, nearly 40% of the annual energy cost of its rapid transit system derives from peak power charges for electric use. By looking closely at total system energy use in real time and making small perturbations to train starts across the system, it might be possible in the future to significantly reduce peak charges with minimal compromise to rider schedules.
Mainline rail transportation organizations in various parts of the U.K. have projected growth of passenger and freight traffic concurrent with replacement of diesel-electric propulsion by pure electric. This situation, together with the closing of aging coal-fired generation plants, has created major problems meeting peak demands on the grid aligned with peak rail traffic demand. An opportunity arises to close demand gaps both by schedule perturbations as in the first example, but also by transiently using on-board or at the wayside battery storage. Although such a remedy depends on emerging battery and high power inverter technology, it will also require advanced controls to manage concurrently the train movement trajectories with energy flow management in the grid to assure grid integrity (voltage, frequency, etc.), proper storage charge/discharge constraints, and schedule constraints for goods and people.

Since 2007, the privately held Class 1 railroads in North America have deployed optimal control strategies to minimize fuel use in heavy-haul freight diesel-electric locomotives. These controls use GPS and other data to create an autopilot function that can be run by crews in a completely decentralized fashion. As railroads move to electrify propulsion even for heavy haul, the same trajectory optimization strategies can be reformulated for the electric platforms, allowing incremental rollout independent autopilots of electric trains, even before full network collaborative strategies emerge; decentralized train-by-train controls work to satisfy grid constraints (including power quality, rate of change of power, regeneration voltage limits) in addition to managing average energy and peak power consumption. Utilities can exploit such trains as they become pervasive, using variable pricing or other demand-response methodologies through expected pervasive communication connectivity.

In New York City, fleets of Federal Express trucks (and, by 2050, other freight delivery carriers that are certain to enter the market) using EV technology require concurrent planning of delivery routes and recharge cycling optimized to meet varying delivery requirements for their customers, while taking into consideration varying electric rates and hard demand limits of the utilities.

Generalization of the controls aspects of these examples is summarized in Figure 3.4.

Figure 3.4 – Elements of transportation-grid integration
3.4.2 Benefits of a solution to the grid-transportation integrated system

Principal benefits of the combined solution are perhaps obvious, but deciding who will benefit requires careful policy/political considerations.

For the transportation entities, the following benefits could be realized:

- Reduced energy consumption (per passenger per km, or energy per ton), total use, and carbon footprint (including emissions) by the transportation system.
- Potential for peak-demand charge avoidance by the transportation system owner/operator (tax savings to rate payers, higher profit margins to shippers).
- Flexibility to increase system throughput for a cost premium when power is available (e.g., transit system response to sporting events).
- Opportunity for revenue recovery from stored energy during peak-grid periods, both on-board and at railroad-owned substations.
- Flexible replanning to accommodate system failures in transportation components or in the electrical grid.

For the utilities (or ISOs, or third-party entities managing delivery), the following benefits could be realized:

- Ability to operate grid with decentralized storage onboard transportation assets, in substations at the wayside, and from parked trains and passenger vehicles not in service.
- Flexibility to use the transportation system as a complex demand-response system for control, when coordinated perturbations to transportation operations can be accomplished with minimal schedule impact.
- Opportunity to be paid with quality-of-service premiums when transportation system operates at the limits of available power.
- Potential to defer investment in infrastructure to supply the transportation system.
- Shared benefit (with transportation) through discounted off-hour storage recharge of EVs or battery subsystems throughout the network.
- More predictable load planning from jointly optimized and updated vehicle driving plans.
- Flexible replanning to accommodate failures in grid components or subsystems.

Advanced controls, together with exciting innovations in power electronics and energy storage, are enablers to simultaneously manage operation of the grid and electric propulsion transportation systems. Such systems can offer substantial benefits to both the electric supply and transportation constituencies in contrast to traditional models of having utilities accommodate whatever load is presented. With the ability to concurrently and dynamically plan operations of the transportation elements from freight and passenger rail, to transit to fleets of personal electric EVs, these future systems will enable reduced overall energy use by the transportation system, provide the ability to accommodate increased penetration of renewables in the supply infrastructure, and assure resilience of the transportation system to accommodate extremes of demand arising from unplanned freight loads or passenger throughput. Developing the required system modeling and control solution methodologies presents formidable challenges, but early solutions—even prototypes—will provide
guidance to battery developers and other storage technology developers as to what energy capacity and power is needed and where they should be placed in the architecture to make integrated grid and transportation controls cost-effective.

3.5 Driver 4: Empowered consumers

Throughout the history of power systems, grid operators have largely worked in the paradigm that supply (i.e., generators) exists to follow all variability in consumers’ demand. This attitude has profound implications for how we design and operate the grid: the size of system peak relative to average power influences how much capacity needs to be built and the levelized costs of existing capacity, and short timescale (subdaily) variability determines how much flexible generation is required to follow ramps in demand and forecast errors.

Also throughout the history of power systems, though electricity prices that follow fixed time-of-use schedules have been common, the price of electricity for most consumers has been independent of the evolution of system conditions on a day-to-day or hour-to-hour basis. For example, if consumers demand more electricity and it requires more expensive generation to do so, the price that consumers pay nonetheless remains the same. Moreover, system operators have had very few tools to reduce demand from customers with their permission; emergency load shedding programs and rolling blackouts are among the system operators’ bluntest tools, and these are used only in the most extreme conditions.

However, a number of changes in technology and society are inspiring a move away from the world of inflexible loads and into a world in which loads become enabled for real-time responsiveness to system conditions. As we will mention in the following list, some of this responsiveness (motivated by dynamic prices or reliability signals) has existed in parts of the commercial and industrial sector for some time, and there are many practical lessons to be learned from that history. However, though we do not yet fully understand all potential benefits, it is possible that the scale of consumer engagement in power systems could be many orders of magnitude greater than it is today.

The drivers are as follows:

1. It is becoming easier to communicate with customers (and the loads they use) in real time; modems and dedicated phone lines are no longer necessary. The obvious enabler is that broadband Internet access is becoming commonplace. However, power line carrier (PLC) technology is improving, as is access to cellular networks. Due to a massive investment by government and utilities, advanced metering infrastructure (AMI, also known as a smart meter) is also becoming commonplace; this technology replaces older analog electricity meters at residences and businesses and has (in some cases very limited) two-way communications abilities. All of these technologies can empower consumers to make decisions based on real-time system conditions by receiving signals (e.g., price, reliability events, other control signals) that can be used within buildings and businesses to inform changes in demand patterns. Some of them (in particular cellular communications and broadband Internet) can also facilitate centralized or distributed feedback control strategies by communicating consumers’ decisions or preferences to other points in the network.

2. Internet and smart phone-based tools for customer recruitment and engagement are becoming cheaper and easier to use, and in many cases are already operated by utilities. For example, an increasing number of utilities use email, Internet, and smart phone access to allow customers to manage their accounts and study their smart meter data. Recruiting customers.
into programs that enable load flexibility, record customers’ preferences (even as they change in real time), and communicate important information can all be done with these types of tools. Though the fixed cost of establishing these types of communication tools might be high, platforms scale with relatively low cost.

3. If it were clear that the market would support it, appliance manufacturers could easily begin shipping Smart Grid–ready appliances en masse. These appliances would have the communications and actuation—and perhaps even computing—equipment required to enable customers (or, depending on the structure of control loops, centralized entities) to shape demand patterns in response to changing system conditions. Some portion of this market might be cultivated with government incentives, regulation, and labeling (e.g., the well-known ENERGY STAR label might in the future apply to appliances that can connect to local area networks.

In the control community there is a substantial amount of attention given to so-called cyber-physical systems (i.e., physical systems whose function is governed by a networked communication and control system). Power systems are an excellent example: the physical layer is the generators, transmission lines, electricity loads, and all supporting hardware; the cyber layer might consist of SCADA systems, real-time energy management systems (EMS), and market operations software and communications equipment.

What is compelling from a control perspective is that empowering consumers, an emerging concept labeled as demand response, puts millions of new dynamical systems—that is, humans, or the responsive appliances they program—into the existing cyber-physical systems’ myriad control loops. In this way, the details very much matter in how the grid will eventually change with the addition of empowered customers, as in these examples:

1. The type of control challenges that arise in the future will depend strongly on the types of signals consumers receive and where decisions to change consumption patterns are made. At one extreme, consumers (or the devices they use that consume electricity) receive a time-varying (or real-time) price that reflects power system conditions. In this case, it is critical to understand consumers and their loads as embedded, autonomous elements of the control system. At the other extreme, consumers could receive a fixed incentive to allow a higher-level control loop to adjust their consumption; the higher the degree of adjustability, the greater the incentive would need to be. These two extremes, to engage the demand side in power system operations, are typically called price-based and direct control strategies, respectively. In the price-based case, we must understand how aggregations of consumers behave when they have potentially enormous amounts of responsiveness and variability. In the direct control case, those making control decisions must understand the dynamics of consumers’ loads and preferences to ensure that they are always met.

2. Power systems operators are accustomed to complete visibility into the operations of all resources in their systems, especially if they are providing so-called ancillary services that facilitate frequency response or recovery from contingencies (as loads can). These resources are connected typically to the system EMS with two second to ten second frequency updates. Most loads are too small for the system operator to follow individually, and in most cases the cost of telemetry will be too high to instrument all consumers’ loads. The way in which consumer empowerment in power system operations will ultimately take shape will depend strongly on how metering requirements are defined and challenges dealt with. Is it possible to
meter only a fraction or an aggregation of responsive loads? Can system operators use statistical models of response rather than direct measurements?

3.5.1 Lessons from the past

Though there are many new challenges to consider, the landscape ahead is not completely unfamiliar. Whereas deployments of Smart Grid–like functions in the residential sector are in the very early stages, larger commercial buildings and industrial facilities (C&I) have been realizing benefits for many years—since well before the popularization of the Smart Grid concept. Here are three key lessons learned based on the Smart Grid pilot projects in the U.S.:

- **Lesson #1: Consumers should own and control their detailed consumption data.** Utility access to consumption data is appropriate and necessary for purposes of customer billing and grid reliability. Beyond these purposes, consumption information must be under the control of the consumer—any sharing must be with their explicit authorization. The C&I community has broadly endorsed this dictum. In some cases, particularly in manufacturing and process industries, companies view their consumption profiles as competition-sensitive and protect this information carefully.

  For homes, consumption data can show if a property has been unoccupied for some time, what the living patterns are of occupants, and, if research underway succeeds, what appliances are being used and when. Most homeowners do not want such information falling into the wrong hands—especially because these wrong hands can be on keyboards anywhere in cyber space!

- **Lesson #2: Consumers should have direct meter access to their consumption data.** Real-time or near-real-time access to consumption data is critical for managing electricity use and expenditures. Even before the advent of smart meters, commercial and industrial companies were investing in AMI technology that could monitor and communicate this information to their energy management systems. Homeowners will also need near-real-time access to monitor and manage their consumption—immediate feedback on the effect of switching loads on and off is one use case. Direct communication of data from smart meters to inside the home is the only feasible approach for providing acceptably short delays (a few seconds). It is also more cyber-secure than convoluted routes through the utility or third-party networks.

- **Lesson #3: Demand management information should be communicated over existing infrastructure wherever possible.** Commercial and industrial customers rely on the Internet and other existing media to obtain price signals and other messages from utilities and service providers. Proposals for large-scale AMI deployment seem to be an unnecessary expense, given this experience. (A small minority of consumers does not have Internet or cellular access and will need to rely on meter-based demand-response communication.)

3.6 Driver 5: Market designs and regulatory paradigms

Since 1978, when the U.S. government began the movement toward deregulation, the past 30 years have witnessed several trends toward privatization, deregulation, restructuring, and reregulation. New markets and institutional designs have affected the system upgrade and investment by allowing
competition in several strategic sectors of the economy, starting with the airlines and followed by railroads, trucking, shipping, telecommunications, natural gas, and banking. Frank Hyneman Knight succinctly stated the philosophy behind this movement: “Market competition is the only form of organization, which can afford a large measure of freedom to the individual. By pursuing his own interest, he frequently promotes that of society more effectively than when he really intends to promote it.” More recently, Prof. Alfred Kahn of Cornell University, who guided the airline deregulation as the head of the Civil Aeronautics Board, expressed it in a different way: “Deregulation is an admission that no one is smart enough to create systems that can substitute for markets.”

Throughout most of the history of electric power, the institutions that furnished it have tended to be vertically integrated monopolies, each within its own geographic area. They have taken the form of government departments, quasi-government corporations, or privately owned companies subjected to detailed government regulation in exchange for their monopoly status. Selling or borrowing electric power among these entities has been carried out through bilateral agreements between two utilities (most often neighbors). Such agreements have been used both for economy and for emergency backup. The gradual growth of these agreements has had the effect that larger areas made up of many independent organizations have become physically connected for their own mutual support.

In recent years, some of the local monopolies have found it beneficial to be net buyers of power from less costly producers, and the latter have found this to be a profitable addition to their operations. For instance, it is typical in the western U.S. and Canada for surplus hydroelectric power to be transmitted south for air conditioning in the summer; while less expensive nuclear power is transmitted northward in the winter when the reservoirs are low or frozen and only nighttime heating is needed in the south. These wide-area sales and the wheeling of power through nonparticipant transmission systems are international in extent, especially in Europe and the Americas. There is evidence of a worldwide drive to use these interconnections intentionally:

- To create competition and choice, with the hope of decreasing prices
- To get governments out of operating, subsidizing, or setting the price of electric power
- To create market-oriented solutions in order to deliver increases in efficiency and reductions in prices

In order to unbundle the monopoly structure of electric power generation in the U.S., its Congress passed the National Energy Policy Act of 1992. National monopolies in the U.K., Norway, and Sweden have been denationalized and unbundled into separate generation, transmission, and distribution/delivery companies. In most approaches to deregulation, transmission is kept as a centrally managed entity, but generation is broken into multiple independent power producers (IPP), and delivery is left to local options. New IPPs are encouraged (or, at least, permitted), as are load aggregators and electric power brokers, both of whom own no equipment, but rather act as deal-makers that operate on commissions paid by the actual producers and users.

The electric power industry has undergone a substantial degree of privatization in a number of countries over the past few years. Power generation growth is expected to be particularly strong in the rapidly growing economies of Asia, with China leading the way.

Drivers often result from local, regional, or and national priorities. For example, the government of India aims at reducing the “aggregate technical and commercial” (AT&C) losses for power distribution systems from 34% to 15%, with an annual target of 1% improvement [17]. In their report, commissioned by the Indian government’s Ministry of Power, an overhaul of the distribution
sector is suggested to serve India’s economic growth and societal needs. The report also puts forth the suggestion of a national institution to drive this effort.

A new energy value chain is emerging as a result of new regulatory environments, new technologies, and new players that encourage competitive markets. In the case of electricity, the value chain proceeds as follows: 1) the chain starts at the fuel/energy source, 2) proceeds to the power generator; 3) continues when the energy is delivered through the high-voltage transmission networks, 4) continues when the electricity is stepped down to a lower voltage onto distribution networks, and 5) finally is delivered to end-use customers for consumption. There are a large number of operational services along this value chain for delivering electricity to customers. Much of the existing focus has been on the supply side to enable competitive wholesale transactions. This focus has resulted in trading floors for energy and capacity sales, as well as promoted open and nondiscriminatory access to the transmission grid. In this new energy value chain, the consumption or demand side of electricity deserves special attention.

Changes in technology and the resulting economics have disrupted the traditional value chain and stimulated the adoption of distributed energy resources (DER). These distributed resources can assume many forms, but some key examples are distributed generation and storage, and plug-in hybrid electric vehicles (PHEV).

A class of service offerings with similar requirements include those related to customer billing, management of customer equipment, energy information, and a range of value-added services. The latter include online meter reading, bill management, energy audits, real-time pricing, and procurement. Many of these service offerings share similar requirements for integrating disparate systems, automating business processes, and enabling physical and financial transactions. Delivering these services will require a communications architecture that is open, highly scalable, and sufficiently flexible and adaptable to meet the changing business needs of suppliers and customers.

### 3.7 Challenges

Each of the drivers in Section 3.2 through Section 3.6 brings with it a host of new challenges for the energy grid. In the context of renewables, limited dispatchability necessitates new solutions that do not lead to increased ancillary services. Their intermittency introduces several operational challenges in terms of requiring significantly higher levels of regulation and ramping capacity. They also introduce new flow patterns at the distribution level, implying drastic changes to the protection, distribution automation, voltage management, and VAR management. In addition, introduction of renewables in dispersed areas might cause a need for transmission expansion. Increased electrified transportation leads to significant new loads on distribution networks, many of which are woefully inadequate when it comes to monitoring and automation, requiring a major overhaul of distribution systems across the globe. Large, distributed loads have the potential to be coordinated with grid operation to manage highly complex interactions that arise from spatial and temporal imbalances between requirements of the transportation network versus what is available from the grid. With price-based mechanisms taking center stage for the transformation of demand into a flexible entity, the challenge that emerges is how true real-time price is to be determined, with ever-changing grid conditions both in generation and in demand. Dangers of monopsony [12] might also need to be avoided. Yet another challenge here is the modeling of empowered consumers without violating privacy or security concerns. A stressed infrastructure implies that with additional demand and intermittent generation, reliability is severely compromised. Innovative methods for achieving and ensuring power balance are needed.
All of these factors imply that the future grid must evolve so as to address the complexity that accompanies high renewable penetration with its attendant intermittency, spatially distributed generation, and new paradigms for collaborative load management, in contrast to how the grid has operated for the past 100 years. Control technology is at the center of this scene and is a key enabling factor in the evolving grid.

3.8 Enabling factors

Paradigm shift in any sphere can occur only if, in addition to compelling drivers that force a different point of view, enabling factors are present that provide novel handles on the problem. In the context of the Smart Grid, technological advances, standards, and policy are key enabling factors that can facilitate global movements toward the Smart Grid (Figure 3.5). These factors are discussed in greater detail in the following subsections.

Figure 3.5 – Global Imperative for cleaner, more efficient, secure, sustainable and affordable energy: drivers and factors in the socio-economic-technological macro environment

3.8.1 Technology

The three building blocks of technology that can propel us towards the Smart Grid objectives are 1) digital advances in information and communication of varied aspects of the grid, 2) innovations in power electronics that allow bidirectional flow and advanced control of all aspects of the grid, and
3) a blueprint for smart management (i.e., control) of this information, enabling decision making at all crucial spatio-temporal locations in the grid. These points are expanded further in the following subsections.

### 3.8.1.1 Information and communication technologies (ICT)

The challenges of increasing demand, intermittencies, and uncertainties can be met only by gathering pertinent information about the grid conditions and communicating them to key locations with minimal latencies. A number of several studies, initiatives, and reports have been carried out on the state of the power grid and its projects, including the Complex Interactive Networks/Systems Initiative (CIN/SI) [3]. The common theme that emerges from these studies is that the end-to-end power grid (from fuel supply, to generation, transmission, and distribution systems, to end-use) can be operated close to the limit of stability by an advanced technology with a better ICT.

- High-speed, fully integrated, two-way communication technologies will make the modern grid a dynamic, interactive mega-infrastructure for real-time information and power exchange. Open architecture will create a plug-and-play environment that securely networks grid components to talk, listen, and interact.

- Emerging sensor technologies will enhance power system measurements and enable the transformation of data into information. They evaluate the health of equipment and the integrity of the grid, and support advanced protective relaying; they eliminate meter estimations and prevent energy theft. They enable consumer choice, enable demand response, and help relieve congestion.

### 3.8.1.2 Power electronics

Several leading applications of science and technology outside the traditional electric energy industry might apply in meeting and shaping consumer needs. These applications might include entirely new technologies, not part of the portfolio of traditional electricity solutions and not identified in other tasks, which could be potentially available as well. Some technology areas include these examples:

- Materials and devices—including nanotechnology, microfabrication, advanced materials and smart devices
- Mesoscale and microscale devices, sensors, and networks
- Advances in information science: algorithms, artificial intelligence, systems dynamics, network theory, and complexity theory
- Bioinformatics, biomimetics, biomechatronics, and systems biology
- Enviromatics: development and use of new methodologies and the use of state-of-the-art information technology for improved environmental applications
- Other industries moving to a wireless world, including transportation, telecommunications, digital technologies, sensing, and control
- Markets, economics, policy, and the environment
- End-to-end infrastructure—from fuel supply to end use
The following list shows examples of higher-level smart structures and systems that can be built from smart materials and used in the grid:

1. **Flexible alternating current transmission systems (FACTS)**\(^8\) FACTS devices are a family of solid-state power electronics devices that provide enhanced power control capabilities to high-voltage AC grid operators. FACTS controllers act like integrated circuits, but are scaled up by a factor of 500 million in power. By applying FACTS devices, utilities can increase the capacity of individual transmission lines by up to 50% and improve system stability by responding quickly to power disturbances. There is a need to reduce the costs of FACTS technology to provide for broader use. One method for reducing the costs is to replace the silicon-based power electronics with wide band-gap semiconductors such as silicon carbide (SiC), gallium nitride (GaN), and diamond.

2. **High-voltage direct current transmission systems (HVDC):** These transmission systems are based on the rectification of the generated AC and then inversion back to AC at the other end of the transmission line. Modern systems are based on thyristor valves (solid-state power control devices) to perform the AC/DC/AC conversions. Conventional HVDC transmission systems have been built with power transfer capacities of 3000 MW and ± 600 kV. A new class of HVDC converter technology has been introduced in the last few years, referred to as voltage source converters (VSC), and is based on gate turn-off switching technology or insulated gate bipolar transistors (IGBT). These devices have higher switching frequency capability. HVDC transmission is used in long-distance bulk power transmission over land or for long submarine cable crossings. Altogether, there are more than 35 HVDC systems.

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\(^8\) FACTS devices are used for the dynamic control of voltage, impedance and phase angle of high-voltage AC transmission lines. These are the main types of FACTS devices:

1. **Static VAR compensators (SVC)**, the most important FACTS devices, have been used for a number of years to improve transmission line economics by resolving dynamic voltage problems. Their accuracy, availability, and fast response enable SVCs to provide high-performance steady state and transient voltage control compared with classical shunt compensation. SVCs are also used to dampen power swings, improve transient stability, and reduce system losses by optimized reactive power control.

2. **Thyristor-controlled series compensators (TCSC)** are an extension of conventional series capacitors created by adding a thyristor-controlled reactor. Placing a controlled reactor in parallel with a series capacitor enables a continuous and rapidly variable series compensation system. The main benefits of TCSCs are increased energy transfer, dampening of power oscillations, dampening of subsynchronous resonances, and control of line power flow.

**Static synchronous compensators (STATCOM)** are GTO (gate turn-off type thyristor) based SVCs. Compared with conventional SVCs (see the first item in this footnote’s list), they do not require large inductive and capacitive components to provide inductive or capacitive reactive power to high-voltage transmission systems. This feature results in smaller land requirements. An additional advantage is the higher reactive output at low system voltages where a STATCOM can be considered as a current source independent from the system voltage. STATCOMs have been in operation for over 10 years.

**Unified power flow controller (UPFC).** Connecting a STATCOM, which is a shunt-connected device, with a series branch in the transmission line through its DC circuit results in a UPFC. This device is comparable to a phase shifting transformer but can apply a series voltage of the required phase angle instead of a voltage with a fixed phase angle. The UPFC combines the benefits of a STATCOM and a TCSC.
operating or under construction in the world today. The longest HVDC submarine cable system in operation today is the 250 km Baltic Cable between Sweden and Germany.

3. **Dynamic Line Rating**: The maximum power that can be carried by a transmission line is ultimately determined by how much the line heats up and expands. The *thermal rating* of a line specifies the maximum amount of power that it can safely carry under specific conditions without drooping too much. Most thermal ratings today are static in the sense that they are not changed through the year. For such ratings to be reliable, they must be based on worst-case weather conditions, including both temperature and wind velocity. Dynamic line ratings use real-time knowledge about weather or line sag to determine how much power can be transmitted safely. Typically, a dynamically monitored line can increase its allowable power flow (ampacity) by 10% to 15% over static ratings.

In the future, smart materials and structures are expected to show up in applications that span the entire electric power system, from power plant to end user. Smart materials, in their versatility, could be used to monitor the integrity of overhead conductor splices, suppress noise from transformers and large power plant cooling fans, reduce cavitation erosion in pumps and hydroturbines, or allow nuclear plants to better handle structural loads during earthquakes.

### 3.8.1.3 Control

The third enabling factor of technology is control, and the central focus of this entire document. As amplified in Chapter 2, control systems pervade the grid, ranging from feedback loops of individual generators to coordinated controls of hundreds of generators across a large region, and affect various performance goals of the grid. As illustrated in the preceding sections in this chapter, several drivers contribute to the complexity of the ultimate goal of the Smart Grid—delivering energy with increased robustness, reliability, efficiency, and quality for consumers. Several centers of activity are currently emerging in the technological front in an effort to realize this goal. Increased penetration of renewable energy is being attempted not only in the U.S., but also across the globe. This greening is accompanied by various innovations in transmission systems and distribution systems. Validation of the delivery of green energy is being explored in small scales through microgrids and virtual power plants. All of these are being investigated through support from extensive, flexible, and diverse demand response, significant advances in power electronics, and distributed community storage, mobile and otherwise. Innovations in market mechanisms and designs that explicitly and implicitly support novel architectures in transmission and distribution are being explored. Grid-wise innovations are being researched to obtain improved efficiency, customized heating and cooling systems, self-healing, and enhanced cyber security.

At the core of each of these centers of activity is a control problem. Control of active power in a wind farm is an attractive method for achieving frequency control in a power grid. Control architectures of various kinds are sought after to achieve various goals in transmission systems. For example, a hybrid architecture that combines centralization and decentralization is of interest to ensure reliability over a wide range and local power balance through dynamic PMU. A distributed control architecture might be desirable to cope with redundancy, and a meshed architecture to ensure protection. Other control problems that need to be addressed in transmission systems are coordinated control of variable generation using FACTS, and reactive power control using distributed renewables. Innovations in distribution systems are centered around control as well. Some examples of control problems that need to be explored are coordinated control of virtual aggregated generation with distributed generation and communication of demand, storage, and generation and of renewable generation and electric vehicles.
In addition to the previous classical systems in the grid, emerging areas represent loci of control as well. At the market level, control is poised to play a new and possibly major role in the coordination of generation and consumption through novel market mechanisms. Using pricing as a feedback signal, novel control methods are being explored for achieving power balance. If price is viewed as a feedback control signal, demand response can be viewed as the corresponding actuator. Design of flexible demand-side entities with varying frequency response characteristics is yet another quintessential control problem.

Storage is yet another area that poses control problems. Time-shifting of loads and storage by careful manipulation of loads and coordination of storage with location of renewable generation are some examples.

### 3.8.2 Standardization and interoperability

The Smart Grid is a systems of systems. Solutions are, and will increasingly be, integrations of components, often from different sources. The components in question are not just physical products, but also communication protocols, information and data models, software implementations of algorithms, etc. It is thus important that components and subsystems from different suppliers can work together (interoperability), in as close to plug-and-play fashion as feasible and consistent with safety and reliability constraints; and that they are based on open, accessible interfaces and protocols (standardization). Interoperable standards are thus a driver for Smart Grid developments; without them, the effort and expense of product development and system integration are increased.

The importance of interoperable standards for the Smart Grid is globally recognized, and end-use sectors are a particular focus. In the U.S., a public-private partnership organization, the Smart Grid Interoperability Panel (SGIP), has been established by the National Institute of Standards and Technology (NIST) “to support NIST in fulfilling its responsibility, under the Energy Independence and Security Act of 2007, to coordinate standards development for the Smart Grid” [16]. Similar initiatives are under way in the E.U. [8] and China [15].

Interoperability and standards can drive the development and deployment of control solutions for the Smart Grid. For example, if a standardized approach to developing control-relevant mathematical models of demand-side equipment was available, demand-response technologies could be implemented with considerably less application-specific customization effort than is involved at present. Similarly, a common approach for communicating control signals such as set point changes and parameter updates would obviate the need for multiple protocol translators and interfaces. The controls research community has not traditionally been active in standardization efforts, but such engagement is crucial for industry uptake of its output.

### 3.8.3 Policy

Given the goals of moving towards a decarbonized society, several studies have been conducted to generate estimates of the least-cost combination of technologies necessary to provide the economy’s energy services, with or without a CO₂ emissions constraint. In a recent analysis at the Electric Power Research Institute (EPRI), two technology scenarios were contrasted: a Limited Portfolio scenario representing incremental technology improvements, and a Full Portfolio scenario representing the electricity technology advances consistent with those used in EPRI’s Prismanalysis [4]. The Limited Portfolio scenario is designed to represent modest improvement beyond the current technologies, but without the availability of carbon capture and storage. The Full Portfolio scenario is designed to
represent substantially more improvement in performance and costs for a range of technologies, thus allowing more widespread economical deployment of these technologies. Table 3.2 illustrates the key differences between the two scenarios. Note that costs do not include any production or investment tax credits for any technologies. Comparing the economy-wide cost of meeting a CO\textsubscript{2} constraint between these two scenarios provides a basis for assessing the value of the RD&D investment needed to assure the levels of technology performance described in the Prism analysis.

\textit{Table 3.2 – Differences between Limited Portfolio and Full Portfolio in EPRI Prism analysis}

<table>
<thead>
<tr>
<th></th>
<th>Limited Portfolio</th>
<th>Full Portfolio</th>
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</thead>
<tbody>
<tr>
<td><strong>Supply side</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon capture and</td>
<td>Unavailable</td>
<td>Available</td>
</tr>
<tr>
<td>storage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New nuclear</td>
<td>Existing production levels</td>
<td>Production can expand</td>
</tr>
<tr>
<td>Renewables</td>
<td>Costs decline</td>
<td>Costs decline faster</td>
</tr>
<tr>
<td>New coal and gas</td>
<td>Improvements</td>
<td>Improvements</td>
</tr>
<tr>
<td><strong>Demand-side</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plug-in hybrid electric vehicles</td>
<td>Unavailable</td>
<td>Available</td>
</tr>
<tr>
<td>End-use efficiency</td>
<td>Improvements</td>
<td>Accelerated improvements</td>
</tr>
</tbody>
</table>

Technology availability has a large impact on the U.S. generation mix. Figure 3.6 compares the generation mix for the EPRI Limited Portfolio and Full Portfolio scenarios. In the Limited Portfolio scenario, emissions reductions require large reductions in electricity demand, which places severe constraints on economic growth. In contrast, in the Full Portfolio scenario, the availability of CCS and nuclear generation provide large-scale, supply-side emissions reductions so that the electricity market is preserved and constraints on economic growth are limited. Consequently, the availability of advanced generation technologies results in a substantially lower projection for wholesale electricity costs—reaching $65/MWh in 2050, compared to $160/MWh if emissions reductions are met under the Limited Portfolio scenario. Note that the 2000 average U.S. wholesale electricity cost was $44/MWh. Hence, the Limited Portfolio would increase electricity prices by about 260%, whereas the Full Portfolio would increase electricity prices by only about 50% over the analysis period. (This analysis assumes a policy is established to stabilize carbon emissions at 2010 levels through 2020 and to reduce carbon emissions by 3% per year through 2050.)
Figure 3.6 – Comparison of electricity prices in the Limited Portfolio and Full Portfolio [10]

3.8.3.1 Global priorities for the Smart Grid

Recent policies in the U.S., China, India, E.U., U.K., and other nations throughout the world, combined with potential for technological innovations and business opportunities, have attracted a high level of interest in the Smart Grid.

Nations, regions, and cities that best implement new strategies and infrastructure might reshuffle the world pecking order. Emerging markets could leapfrog other nations:

1. **U.S.** investment is upwards of $9 billion spanning federal awards of $3.4 billion in Smart Grid Investment Grants (SGIG) and $1.6 billion in Smart Grid demonstration projects [4].

2. **China** has invested $7.3 billion and will spend $96 billion in Smart Grid technology by 2020 [4].
   - China’s energy needs are expected to double by 2020.
   - China will account for 18.2% of global Smart Grid appliance spending by 2015.

3. **South Korea** has invested nearly $1 billion [4]:
   - A $65 million pilot program on Jeju Island is implementing a fully integrated grid for 6,000 homes, a series of wind farms, and four distribution lines. Its leaders plan to implement Smart Grid infrastructure nationwide by 2030.

4. **Latin America** [13]
   - **Brazil**: 60% growth in electricity consumption between 2007 and 2017 with 16% to 34% increase in renewables from hydroelectric, biomass, and wind. However, Brazil has
an aging grid with a power flow that is currently one way and needs to become bidirectional.

- Push from the regulator: mandatory replacement of 65 million meters starting in Q4 2012, and the new regulation of time of use (TOU) tariffs for residential customers, aiming to reduce peak load.
- Utilities launching several smart metering pilots and distribution automation projects.

- **Mexico:** Comisión Federal de Electricidad (English: Federal Electricity Commission), or CFE, is acquiring a pilot for 23,000 meters in order to better understand the technology and prove the benefits. After CFE took over Luz y Fuerza del Centro concession area, the ultimate goal is to achieve higher quality/reliability indicators in the Mexico City metro area.

- **Chile:** Customers in Chile are looking at the Smart Grid as a solution to reduce losses, improve quality of service, and increase operations efficiency. Rather than transferring the implementation costs as a tariff, having Smart Grid as a service is the most likely option for consumers requesting reliable power.

- **Colombia:** Colombia has approximately 16% commercial losses, and utilities are looking for ways to both reduce fraud and increase operational efficiency.

- **Puerto Rico:** The Puerto Rico Electric Power Authority (PREPA) is looking at the Smart Grid as a means to increase competitiveness of the electricity supplied against independent power producers. Puerto Rico aims to drive dependence on oil from 70% to 50% by 2015, and down to 26% by 2025.

- **Argentina:** Customers in Argentina are awakening to the Smart Grid technologies, limited by tariffs/regulations. Ultimate objectives are increasing efficiency, quality of service provided, and peak load shaving.

- **Uruguay:** Usinas y Terminales Eléctricas (UTE), Uruguay’s state power company, has a strong renewables matrix and is looking for robust demand-response solutions for peak load shaving and controlling the demand on the consumer side.

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*Figure 3.7 – Latin American drivers for Smart Grid [13]*
In addition, industries involved in developing and managing Smart Grid technologies range from telecom, IT, semiconductors and equipment manufacturers to traditional energy suppliers, for example:

- Siemens Energy plans to double its current growth rate in the Smart Grid sector to capture $8.48 billion in global business over the next five years, including an open platform to manage the wholesale delivery of power between utilities and grid operators.
- Cisco is focusing on grid management, substation automation, and energy management systems, and is expecting $15 billion to $20 billion in global opportunities over the next seven years by joining electrical infrastructure with IT.
- Alcatel-Lucent is using its experience in energy-utility telecom and data networks to build and manage the sophisticated, mission-critical IP communication networks required by the Smart Grid, and is driving a great deal of research on the topic.

Global investment in the Smart Grid, including smart meter implementations, upgrades to the transmission, and upgrades to distribution (T&D) infrastructure, will reach the following levels:

- **Lowest forecast.** Approximately $46 billion by 2015 [1]: T&D investments will be the lion’s share of Smart Grid investments through 2015; on a cumulative basis, a total of almost $41 billion will be invested globally in the T&D infrastructure through 2015, compared to $4.8 billion for the purchase and installation of smart meters.
- **Mid-range forecast.** Approximately $200 billion in global Smart Grid investment expected by 2015—almost $53 billion of that in the U.S. alone [14].

Factors that boost Smart Grid investment and technology in the short term:

- Analytics: mining data to increase understanding.
- Standards consolidation.
- Increasing penetration of solar and electric vehicles: demand shifts, integrate new tools and technologies.

### 3.8.4 Political barriers

The current absence of a coordinated national decision-making body is a major obstacle for Smart Grid development in the United States. States’ rights, and state public utilities commission regulators have removed the individual states’ utility motivation for a national plan.

The effect federal and state policy has on the proliferation of any energy related technology is substantial. Energy policy drives the legislation and regulations that enforce what, how, and where energy resources are used. Therefore, among others, energy generation stakeholders can be affected by specific regulations, and consumers can be affected by the amount and quality of services offered.

Because elected federal and state officials drive these policies, the multiple-year cycle of government changeover has a large impact on both current and future policy decisions. Energy independence, clean energy, environmental impact, jobs, public opinion, and corporate opinion are a few of the many political factors weighed in the decision-making process of government.

The economic payback of Smart Grid technologies in the U.S. is three to seven times greater than the money invested. Further, the payback starts with the completion of each sequence of grid
improvement. The issue is not merely who invests money (because that is ultimately the public), but whether it is invested through taxes or kilowatt-hour rates. Considering the impact of regulatory agencies, they should be capable of inducing the electricity producers to plan and fund the process, which might be the most efficient way to get Smart Grid in operation.

3.9 Summary

Customized and cost-effective advancements are both possible and essential to enable smarter and more secure electric power infrastructures. For example, advanced technologies now under development or under consideration hold the promise of meeting the electricity needs of a robust digital economy. The potential exists to create an electricity system that provides the same efficiency, precision, and interconnectivity as the billions of microprocessors that it will power.

However, considerable technical challenges, as well as several economic and policy issues, remain to be addressed. At the core of the power infrastructure investment problem lies two paradoxes of restructuring—one technical and one economic. Technically, the fact that electricity supply and demand must be in instantaneous balance at all times must be resolved with the fact that new power infrastructure is extraordinarily complex, time-consuming, and expensive to construct. Economically, the theory of deregulation aims to achieve the lowest price through increased competition. However, the market reality of electricity deregulation has often resulted in a business-focused drive for maximum efficiency to achieve the highest profit from existing assets and does not result in lower prices or improved reliability. Both the technical and economic paradoxes could be resolved by knowledge and technology.

In summary, automation and control systems are needed across broad temporal, geographical, and industry scales—from devices to power system-wide, from fuel sources to consumers, from utility pricing to demand response. With increased deployment of feedback and communication, opportunities arise for reducing consumption, for better exploiting renewable sources, and for increasing the reliability and performance of the transmission and distribution networks. At the same time, however, closing multiple loops where they have never been closed before, across multiple temporal and spatial scales, creates control challenges as well.

These challenges require a multitude of research expertise that have to be brought to bear, including control theory, stochastic optimization, dynamic programming, complexity theory, social network theory, graph theory, optimization, probability theory, economics, game theory, international economics, engineering design, fault-tolerant system design, computational science, information theory, communications, organizational science, policy and market designs, coordination science, behavioral science, and human behavior. These disciplines need to be incorporated within the approach with mathematical rigor, which the control community is eminently qualified to create.

As the world grows more interconnected, we are becoming surrounded by complex networked systems. Similar to electric power grids, which are the focus of this document, many critical infrastructures are complex networked systems, including these examples:

- Oil and gas pipelines
- Telecommunication and satellite systems
- Cyber infrastructure
- Transportation networks
• Banking and finance systems
• State and local water supply, emergency, and other services

Every one of the previous systems, including power grids, consists of numerous components interlinked in complicated webs [2, 10]. As a result of the number of components and their intricate interconnections, complex networked systems are extremely difficult to design, analyze, control, and protect. Analysis and modeling of interdependent infrastructures (e.g., the electric power grid, together with protection systems, telecommunications, oil/gas pipelines, and energy markets) is especially pertinent. Management of disturbances in all such complex interdependent networks, and prevention of undesirable cascading effects throughout and between networks, requires a basic understanding of true system dynamics, rather than mere sequences of steady-state operations. A better understanding of the dynamics of such complex networks is warranted in order to enhance security, quality, reliability, and availability (SQRA) of the overall system.

Specific attributes of SQRA are needed for electricity to meet the needs of the evolving digital society. Reliability and uninterruptability are practical necessities in digital enterprises. The digital society is expected (and designed) to be continuously operational, without interruption or denial of service. The interface between digital systems, processes, and enterprises and electric power delivery must support this reliability, with innovations spanning from the generation sources to the microchip. Similarly, availability of power is also a necessity. Although higher reliability is nearly always a key objective for electric power suppliers, availability is the parameter with which users of sensitive digital equipment and processes are most concerned. Effective, intelligent, distributed control is an essential ingredient to assure such SQRA.

3.10 Citations


4.1 Introduction

The Smart Grid portends revolutionary changes to the generation, delivery, storage, and use of electricity. A revamped and redefined electricity infrastructure will be more dynamic, flexible, reliable, and robust. Modeling and identification, estimation and optimization, feedback and adaptation, and other control technologies and concepts will be key enablers. The transformation will not occur overnight—substantial research and development will be required, building on the investments that have been made, and continue to be made, in the initial stages of Smart Grid activities worldwide. We consider smart meters, phasor measurement units, power electronics, and
other developments underway as providing the foundation on which control can construct the future Smart Grid that truly merit the name!

In this chapter, we paint a number of futuristic control-enabled scenarios in several areas of the Smart Grid, contrasting the visions with today’s state of the practice. We believe advances in control science and engineering will be crucial for realizing the scenarios, which thus suggest exciting and important directions for research in the field. Our first scenario outlines a radical rearchitecting of the power system and is developed in some detail. Subsequent scenarios focus on specific Smart Grid areas, including markets, demand response, microgrids, transportation, distribution, transmission, and renewable generation. These sections include capsule summaries of the challenges and research opportunities involved, with more detailed discussion deferred to Chapter 5.

4.2 Scenario 1: Grid-scale real-time endpoint-based control

4.2.1 2040 vision: The rearchitected grid

In the last three decades, the power network, from generation to transmission and distribution to consumption, has undergone the same kind of architectural transformation that computing and communication networks went through at the end of the twentieth century during the development of the Internet. The transformed power network is defined by two characteristics:

1. Hundreds of millions, perhaps billions, of active endpoints: sensors, actuators, and communication devices are deployed at generators, along transmission lines, at substations, in transformers, in distributed energy resources (DER) such as photovoltaics and wind turbines, and in inverters, storage devices, electric vehicles, microgrids, premises, and smart appliances in distribution networks.

2. Millions of individual and institutional agents: stakeholders in the operation of the new power-ICT (information communication technology) grid include industrial, commercial and residential customers, governmental and university campuses, microgrids, utilities, power generators, energy services companies, and regulators.
The majority of the endpoints in the grid are not merely passive loads (as used to be the case in the circa-2010 grid), but endpoints that generate, sense, compute, communicate, and actuate. Although these hundreds of millions of distributed energy resources introduce rapid, large, and random fluctuations in power supply and demand, voltage, and frequency, we have turned this challenge to our advantage, using advances in control and optimization technologies to coordinate these mega-scale resources so as to optimize their operation, and fulfill societal objectives for energy and the environment.

Endpoint-based grid operation (Figure 4.1) relies on ubiquitous sensing, fast computation and actuation, and extensive data analytics. These form the basis for real-time feedback control as well as for new market mechanisms and business models. Intelligence is embedded everywhere, from electric vehicles (EV) and smart appliances to inverters and storage devices, from homes to microgrids to substations. Decisions are made locally, but coordinated globally.

### 4.2.2 Fundamental limitations and new enablers, circa 2010

The control paradigm is incompatible with our future vision of a grid-scale coordinated network of DERs (see Figure 4.2):

1. **Today, global control is slow, open-loop, centralized, human-in-the-loop, deterministic and worst-case preventive.** At the transmission level, the energy management system (EMS) coordinates system-wide decisions based on SCADA data from substations and optimizes global objectives such as minimizing power loss or generation cost. Utilities have also used pumped storage to balance transmission system operations and economics (e.g., water is pumped up a dam at night and down during peak hours). At the distribution level,
traditional Volt/VAR control is designed mainly to cope with the slow variation in aggregate load (hourly and daily routines). Demand-response programs generally target large industrial or commercial users and at most 30% of the residential users with air conditioning and/or electric water heating. All of these control operations are characterized by slow timescales, open-loop scheduling, and centralized information and decision making, the opposite of what is needed to control and optimize the large network of DERs that we envision.

2. **Fast timescale (cycle time) control is local and oblivious of the global condition.** This condition is exemplified by mechanical protective relays that trip based on local current, and some frequency and voltage regulation mechanisms. The lack of global situation awareness is the leading cause for disturbances to cascade into blackouts; indeed, the postmortem analysis of the 2003 U.S. Northeast blackout lists “inadequate system understanding” as the primary cause of the blackout. Moreover, fast timescale control is used primarily for protection against faults and is rarely invoked as a means to optimize normal operation. Rapid control is required to manage a large network of active DERs.

![Figure 4.2 – Today’s approach is based on a centralized, global perspective over a slow timescale and decentralized, fast-timescale local mechanisms that are oblivious of global conditions. The proposed endpoint-based scalable control complements these mechanisms and combines the advantages of both.](image)

We illustrate here, using an example of Volt/VAR control, how a real-time feedback control algorithm can dramatically improve reliability and efficiency of a distribution circuit over the current standard (IEEE Std 1547™) for inverter control. This example is taken from a Southern California Edison (SCE) project to develop an optimal inverter-based VAR control algorithm for one of their 12 kV distribution feeders with high photovoltaic penetration to minimize power loss and energy consumption (conservation voltage reduction). The circuit has a peak demand of about 10 MW and is located in an industrial area. Five large warehouse rooftop PVs have already been installed, with a total maximum generation capacity of 6.4 MW.

Using real data on load and solar power in the Southern California area in the United States, we compare the performance of real-time optimal inverter control with that specified in IEEE Std
IEEE Std 1547™. Here, a *bad state* has a poorer power quality and a higher chance of a fault or an outage. Simulation results show that the distribution circuit will spend an average of 840 hours a year in bad states under IEEE Std 1547™ where voltage or power flow specifications are violated versus zero hours under real-time control.

![Distribution of System State (Solar vs Load)](image)

**Figure 4.3** – *The time the distribution circuit spends in a state in a typical year. A state is defined by load (from SCE data) and solar output (from meteorological data). Red indicates states frequently visited and dark blue indicates those never visited. The white line delineates the limitation of IEEE Std 1547™: all states above the white line are “bad states” under IEEE Std 1547™ where the circuit spends 840 hours a year. No state is a “bad state” under our algorithm.* [3]

In summary, the current control paradigm is centralized with infrequent actions, involving a small number of control points. Such a simple system is sufficient for today’s power system—which, for example, has relatively few active endpoints (e.g., about 9,000 large generators) and demand-side management actions are computed centrally and only invoked during a few hot summer or cold winter days. The lack of ubiquitous sensing, control, and two-way communication in the current infrastructure prevents the participation of a large number of devices/users. Thus, with neither a pressing need nor the technical capability for a distributed, coordinated control architecture, a centralized and static mechanism has evolved to deal with the occasional need to control a few devices/users.

Both need and capability are changing, however. Increasing penetration of wind and solar power, with their rapid and random fluctuations, implies that the basic approach to control must be real-time and closed-loop. The current approach of centralized, slow timescale (hourly and up) and open-loop control cannot cope with significant wind and solar penetration. The large and uncertain demand of EVs means that their charging must be actively coordinated. Studies have shown that, if no regulation on EV charging is implemented, even a 10% penetration of EVs could cause unacceptable variations in the voltage profiles. On the other hand, many studies have also demonstrated that adopting smart charging strategies can mitigate some of the integration challenges and defer infrastructure
investment needed otherwise. The large number of DERs that must be managed means that information must be decentralized and control must be distributed.

Second, the foundation for a new approach is being laid today. The large-scale deployment of a sensing, control, and two-way high-speed communication infrastructure including GPS-synchronized PMUs and AMI is currently under way around the world. In addition, the rapid and continued advances of power electronics will provide the needed platform for ubiquitous sensing, computation, communication and control. For instance, unlike traditional distribution devices that are switched only a few times a day, the inverters that connect photovoltaics (PV), wind turbines, or batteries to the grid can pull or push reactive power at a much faster timescale and with a much finer resolution.

Existing and planned ICT infrastructure, if integrated with the power system, will allow us to monitor and control 1,000 times faster than done today. Indeed, in 2010 the International Energy Agency forecast $6.9 trillion in electric grid modernization globally through 2030; of that amount, Cisco estimates about 25%, or about $1.7 trillion, will be in related ICT infrastructure. As infrastructure deployment proliferates, the new bottleneck in the exploitation of ICT on a massive scale will be the need for overarching frameworks, foundational theories, and practical control algorithms to manage a fully ICT-enabled power network.

We note also that dynamic adaptation by hundreds of millions of end users on a subsecond control timescale, each contributing a tiny fraction of the overall traffic, is being practiced every day on the Internet in the form of congestion control. Even though both the grid and the Internet are massive distributed nonlinear feedback control systems, there are important differences in their engineering, economic, and regulatory structures. Nonetheless, the precedence of the Internet augurs for a highly scalable, dynamic, and distributed control architecture for the Smart Grid. A central task for the Smart Grid, as it was for the Internet, is the development of architectures that support up to billions of active endpoints.

4.2.3 Design principles and research challenges for a new control paradigm

To realize the endpoint-based control architecture, the following challenges need to be addressed:

- Distributed, real-time closed-loop architectures that accommodate uncertainties in renewable generation and match supply to demand by making use of ubiquitous real-time information, and decomposing global objectives into coordinated local algorithms
- Scalable algorithms that are decentralized and deployable at a huge distributed scale supported by local decisions and global coordination
- Integration of economics and distributed control policies to incentivize and align all stakeholders to realize global outcomes
- Interlacing of grid specific cyber security measures to protect against possible vulnerabilities due to a necessary and extensive introduction of ICT
- New mathematical frameworks that combine engineering and economics, combine control and optimization, and engender robustness of massively networked large-scale systems
4.3 Scenario 2: Dynamic pricing and multiple-horizon power markets

4.3.1 The envisioned future: Power generation and demand as equal market participants

It is 2030, and the historical asymmetry in the participation of generation and demand in early power markets has been overturned. Power markets used to be restricted to primarily central generation participants engaging in high-voltage, active-power transactions, with significant limitations for their effectiveness in realizing renewable penetration and grid reliability—but no longer. A radical market reform resulted from the realization that both generation and demand are implicated in the need for reserves, transmission line congestion, and voltage support, and thus both have a role in optimizing power system efficiency. The Smart Grid has enabled full power market participation of both generation and loads—be they large-scale centralized entities or small-scale distributed entities. In other words, distributed loads and generation (e.g., rooftop PV, small wind turbines) have access to high-voltage power markets on par with centralized generation and large wholesalers/load aggregators, while responding to and affecting distribution network costs and power quality requirements.

Market reform has also occurred in the timescales on which markets operate. The cascading timescales—day-ahead, hour-ahead, minutes-ahead, and seconds-ahead transaction horizons—with separate, incomplete, and often inconsistent market mechanisms employed for each, have given way to a broader and seamless spectrum of market and reserve choices. Even the gap in timescales between market-based reserve pricing and centrally coordinated reserve management has been bridged.

Systems and control concepts and technologies have been key enablers. Distributed coordination is now accomplished with dynamic models and optimization algorithms across a broad class of market-facing assets. Buying and selling covers active as well as reactive power. Markets operate at distribution as well as transmission nodes. The old static locational marginal pricing model has given way to a dynamic charge that incorporates real-time prediction of transmission and distribution congestion as well as power quality, carbon emissions, and even the state of equipment such as distribution transformers.

The social benefits of the new market mechanisms are apparent and substantial. They include a reduction in the power reserves that are required for green power-based electrification of transportation (the nation has not imported any oil for the last few years), longer lifetimes for transformers and other equipment, and brownouts and blackouts effectively becoming events of purely historical interest!

Figure 4.4 contrasts our vision with the state of electricity markets in 2020.

4.3.2 Market reform for load-side participation and distributed prosumers: Implications and challenges

In our “oracle” on future markets, we assume that they will develop so as to capture social benefits obtainable with the requisite evolution to competitive markets that: 1) discover clearing prices that reflect costs; 2) allow centralized as well as decentralized generation, loads, and resources (e.g., storage and power electronics accompanying HVAC, PV, and EV that have been put to dual use as
VAR compensators) to participate on a par basis; 3) enable generation, loads, and resources to buy and sell real power, reactive power, and reserves; and allocate real and reactive energy, congestion, and reserve costs to participants according to their marginal responsibility in imposing or relieving these costs. A related market issue is the dynamic optimal control of transmission and distribution (T&D) network connectivity and FACTS resources to minimize the cost of maintaining real-time energy balance reliably while observing congestion constraints. Because the T&D network is a natural monopoly, both its design/expansion/maintenance as well as its optimal dynamic operational control will be primarily centralized tasks aimed at maximizing social welfare. The clearing of competitive markets and the associated social welfare and distributional impacts are tightly coupled to T&D network management.

![Market participation in the power system](image)

**Figure 4.4 – Market participation in the power system today (top) and in the future (bottom).**

Today, centralized generation is the primary full market participant, engaged in two-way communications with market operators; other generation and the consumer sector can provide information to the market but are generally not involved in bilateral market interactions. We envision all players being full market participants in a few decades. The vertical bars represent the notional and relative size of generation/consumption capability; enabled by market expansion, generation will no longer be almost entirely dependent on large centralized plants.

The social welfare implications of well-designed competitive market mechanisms include the examples:

- Cost of electricity will be lowered, even as reliability is increased as a result of demand-side supply of power (real and reactive) and reserves.
• Synergies between the high penetration of renewable generation and the expansion of flexible loads will be realized. Loads such as electric vehicles and other electrified transportation can use cheap and clean renewable generation while providing reserves that mitigate the volatility of clean generation and respond to distribution congestion.

• Marginal cost pricing of VAr compensation provided by power electronics in EVs, rooftop PV, and variable speed HVAC motors will lower distribution network losses and improve effective voltage control.

• Real-time sensing and pricing of distribution network congestion costs (e.g., through transformer usage/hottest spot temperature) will lower distribution network maintenance costs and increase reliability, resulting in resilient infrastructures.

Key market mechanism reforms/evolutions will need to be adopted to allow the realization of the aforementioned benefits. Two specific areas for reform are noted in the next subsection. These encompass numerous technological challenges for control theory and technology.

### 4.3.3 Important challenges and research topics for power market scenarios

#### 4.3.3.1 Multiperiod markets
Understanding and modeling electricity user utility is of paramount importance. In particular, the utility of new flexible loads such as HVAC, EV battery charging, and other storage-like schedulable loads involves intertemporally sensitive dynamics because the service rate at a particular time is a function of the past consumption trajectory. The ability to capture the fact that the utility of these flexible loads is not an additively decomposable function of period-specific electricity consumption is of paramount importance. In fact, it is a prerequisite for correctly modeling the elasticity of flexible load demand in multiperiod power markets. The day-ahead market, clearing hourly generation and demand on day \( d-1 \) for each hour of day \( d \), is the key element in cascaded power markets and the multiperiod market responsible for short-term planning and operational decisions. Given that day-ahead markets today allow only time-additive utility modeling through uniform price quantity bids by each participant for each of the 24 hours, extension and revision of market rules must be analyzed for stability, social welfare optimality, and fairness before they are implemented. The new participant bid process market rules will augment or supplement existing price-quantity pair bids with additional bid options, including participant-state-based utility bids and risk associated with intermittent renewable generation volatility. For example, renewable energy (e.g., wind) forecast error and its statistical properties (those relating aggressive renewable generation bids to additional reserve requirements) should be proposed and analyzed. Gaming, strategic behavior, stability, tractability of market clearing algorithms and social optimality of multiperiod markets must be carefully modeled and investigated.

#### 4.3.3.2 Distribution-network-connected load clearing prices
Distribution network costs and congestion will need to be incorporated in prices available to distribution network-connected consumers and producers, or prosumers. Monitoring of low-voltage consumption and generation (real and reactive) as well as the state of the distribution network (e.g., transformer usage, voltage magnitudes, power flows, and losses) can allow the determination of an extended version of real and reactive local locational marginal prices (LMP) that reflect marginal real and reactive power losses, marginal impact on transformer usage, and marginal impact on location-specific voltage magnitudes. These cost components, together with the relevant high-voltage dynamic
LMPs can constitute a T&D price that captures 1) transmission energy and reserve opportunity cost (including congestion), 2) transmission marginal congestion cost, 3) distribution marginal congestion cost, 4) distribution line losses, and 5) competitive distribution network reactive power costs. Designing these integrated high-voltage transmission and medium-voltage/low-voltage distribution markets is a major challenge that combines algorithmic, computational complexity, state identification, and behavioral issues.

4.3.3.3 Other control-related issues

Control and systems theory research is uniquely qualified to contribute to the science base that will support future power market scenarios. The following nonexhaustive list describes key building blocks of this science base. Modeling abstractions employed must capture in a synthetic manner the following information: 1) the market scenario characteristics described previously, 2) power system physics, 3) critical smart grid-related technologies, and 4) distributed loads and resources that might enable significant social welfare gains. Specific topics for research include these topics:

- Multiperiod market equilibrium in the presence of friction and uncertainty and complex intertemporal as well as uniform participant bids
- Optimal market bidding of local flexible load aggregators for energy and reserves observing local distribution constraints, and optimal self-scheduling of storage resources in multiperiod markets
- Microgrid-enabled virtual markets for the distributed control of regulation service reserve management in response to a centrally determined and broadcast regulation signal

4.4 Scenario 3: Real-time, closed-loop, ubiquitous demand response

4.4.1 A control-centric demand-response vision

It is 2030, and the term demand side has been a misnomer for several years. Customer facilities integrate not just loads, but distributed generation and storage resources as well. All of these energy assets are modeled with their dynamics and uncertainties formally captured and integrated with control and optimization methodologies. As a result, loads, storage, and generation resources, whether in homes, buildings, or industry, respond in real time to the state of the grid, the variation of grid-level renewable generation, and other factors that traditionally were little more than disturbances in old-style facility energy management.

Considerable complexity is hidden from view in this vision, with advanced control technologies ensuring that operational staff in utilities or in facilities do not need to have a hands-on role. For example, fixed, schedulable, and curtailable loads are recognized and modeled, so that they can be run at appropriate times and at appropriate levels. The connection between thermal storage and electricity storage is recognized by the automation system—precooling or ice storage happens automatically and optimally. Production from on-site renewable generation sources is forecast, incorporating dynamic uncertainty, and these forecasts inform the demand-response strategy.

These and other modeling and control actions take place on multiple timescales, from seconds to days or even weeks. Fast dynamic response enables facilities to provide the full range of ancillary services,
including spinning and nonspinning reserve, frequency regulation, and reactive power support. Utilities and system operators regularly exploit this capability, allowing them to reduce their dependence on the natural gas turbines that they used to have online with low capacity factors—an expensive alternative.

Thanks to automation, changes in electricity consumption in consumer facilities are often not the result of manual actions by homeowners, tenants, or building or industrial operators. It’s not uncommon, for example, to have lights in unoccupied homes dim or turn off automatically, HVAC temperature set points automatically adjust, or electric hot water heaters initiate preheating. Such actions are not imposed by the utility; occupants and owners are in complete control. But they have agreed to have various actions taken by their facility EMSs under specified grid conditions and for certain incentives, as communicated by the utility through demand-response programs. Individual (for homes) and organizational (commercial and industrial) needs and preferences are taken into account. The incentives are not just economic—environmentally conscious homeowners allow their temperature set points to be raised in summer when wind energy is in short supply.

The sophistication of control technology has reached a level that enables sites to be dynamically aggregated and disaggregated for automated demand-response (ADR) programs. This ability has become especially important with the development of plug-and-play energy assets. New refrigerators, water heaters, dishwashers, and other appliances are ADR enabled; they are recognized and configured for automated demand response by the EMS upon installation.

4.4.2 A far cry from 2012 demand-response implementations

In comparison to the future vision, the state of demand response today seems antiquated. Most applications still rely on manual communication. Building operators will get a telephone call from the utility asking for certain levels of consumption relief, for example.

Although automated demand response is a hot topic, today’s technology is very much at the 1.0 stage. Setting up an automated demand-response program, for example, requires coordinators to prepare and review checklists of what actions can be taken under which conditions. Discussions between building owners and demand-response providers take place to determine, for example, that at certain pricing levels, certain lights should be turned off, at other levels some elevators should be disabled, and at yet other levels, HVAC energy reductions should be effected. The actions are limited to loads; storage and distributed generation are not included. Furthermore, the loads involved must be predetermined; dynamically including and excluding loads from programs is not readily accomplished.

The delays involved in the process—in negotiating agreements, issuing commands, actions being taken, and measurements being reported—preclude real-time responsiveness. Dispatching for ancillary services is in the process of first demonstration but is far from large-scale implementation.

Much of the challenge comes from the lack of appropriate equipment in many facilities. The vast majority of commercial buildings still lack an EMS. At least a rudimentary one must be installed and commissioned before automated demand response, even in its 1.0 stage, can be implemented—and similarly for the instrumentation needed for measurement and validation, such as submetering.

Implementing automated demand response today is complicated enough that only large facilities can directly engage in programs. For small facilities, aggregators must individually sign up customers, provide the infrastructure required, and serve as the intermediary between the independent system
operator/utility and the customer. The complexities, delays, and costs involved with this business model limit the penetration of automated demand response today for small-scale consumer facilities.

4.4.3 Research and development challenges and opportunities for control science and engineering

The technology gap between today’s state of the art and the vision outlined previously suggests that much research is needed if our ambitious goals are to be realized. Control science and engineering have a major role to play. Indeed, our vision of demand response can fundamentally be seen as an expanded control problem (Figure 4.5).

Figure 4.5 – Schematic, simplified illustrations of traditional (top) and envisioned (bottom) power systems. In the envisioned future, through automated demand response, facility energy resources can help manage the uncertainty that arises with renewable generation. “Negawatts” take on significant importance—reducing demand is equivalent to increasing generation—hence the bidirectional power flow shown. (f: frequency; V: voltage; $: prices; u: control actions)

This control-centric Smart Grid perspective suggests several areas of research for control scientists and engineers for widespread and real-time automated demand response. These areas are summarized in the following subsections and discussed in greater detail in Chapter 5.
4.4.3.1 **Dynamic models of facility energy resources**

For this vision to be achieved, electricity consumption (and energy consumption more broadly) and performance of a vast variety of facility-based devices and systems must be modeled with specific attention to various dynamical aspects. These include startup and shutdown; changes in state, delays, and time constants; dependencies on environmental factors and among related systems; efficiencies and usage guidelines at different operating points; and the ability to curtail and schedule. The dynamics and behavior of load, storage, and local generation assets will need to be captured in a formulation that permits their incorporation and coordination in optimization and control frameworks.

4.4.3.2 **Forecasting methods for loads and weather**

The main sources of uncertainty that are of interest for realizing the future vision of demand response are weather and consumption. The two are closely related in that consumption in homes and buildings has substantial dependence on weather. However, the two phenomena are qualitatively very different and require different modeling and forecasting approaches.

4.4.3.3 **Human and organizational response**

A fascinating aspect of including end-use sectors in Smart Grid engineering is the necessity of modeling people—as consumers as well as facility operators and occupants—as elements of control systems. There is considerable variation in populations that will also need to be captured, both in physiological responses (e.g., sensitivity to temperature and humidity) and in cognitive processes such as latency, learning, fatigue, and the willingness to trust automated controllers that implement personal preferences.

4.4.3.4 **Performance and stability of coupling markets and electricity flows**

Real-time and closed-loop demand response will result in a coupling of power flows and markets at timescales that have the potential to cause instability. The controls community has the ideal background to take a leadership role in defining and analyzing pricing structures, policies, algorithms, and constraints. It must be emphasized that this problem is not purely financial but rather one that integrates physical, cyber, social, and environmental aspects. Stability and performance must be maintained both for prices and for power flows in the grid.

4.4.3.5 **Full provision of ancillary services**

In principle, demand-side management, with appropriate assets and instrumentation, can serve the same range of services as generation plants. In particular, increasing implementation of distributed generation and storage technologies (including electric vehicles) might allow the full spectrum of ancillary services to be served by customer facilities in an automated fashion. New challenges that arise in this context include the consideration of real as well as reactive power, bidirectional power flows, and multiple-timescale coordination, requiring fundamental advances in feedback/feedforward and regulatory/ supervisory control strategies.
4.5 **Scenario 4: Smart periphery—coordinated and hierarchical microgrids**

4.5.1 **A vision for energy-efficient microgrids**

It is the year 2030, and the grid of 2012 has been fully replaced by millions of interconnected microgrids that collectively ensure grid reliability. Each microgrid is a largely self-sufficient subsystem that fully uses small, green generation capacity and, in addition, routinely provides green reserve capacity. Blueprints for reliable and affordable microgrids have been laid, thanks to the congruent developments in 1) distributed, renewable, generation, 2) distributed, hierarchical, and robust control theory, 3) advanced communication and networking, 4) advanced monitoring units, 5) demand-response modeling and prediction, and 6) distributed community storage. Broadly, radical innovations in microgrids have occurred at two levels: intermicrogrid coordination and intramicrogrid management.

4.5.1.1 **Coupled and coordinated microgrids—a decentralized perspective**

Load-balancing centers located in microgrids have replaced ISOs as the decision centers. They provide coordinated, distributed support for reliable and affordable power. Significant coordination occurs at these centers based on a suite of models, dynamic pricing strategies, storage models, and deferrable demand. The underlying control strategies are organically tied to market transactions carried out at the wholesale and retail level, from day-ahead to real-time settlements. Volatility in load balancing is a historical footnote. A dynamic framework carries out financial settlements in the coupled microgrids. These settlements are robustly designed to accommodate installation of new renewable sources in scheduling generation, demand-response-compatible loads, and distributed community storage banks, as well as their efficient day-to-day functioning.

On the other hand, the simultaneous evolution of microgrids from both a top-down management strategy, in which the high-level framework of the system is formulated by a grid operator, and a bottom-up one, in which the piecing together of systems gives rise to grander systems, transforming economic dispatch from a centralized to a distributed model. Microgrids have been organized hierarchically, some of them managed by the utility grid and others by the microgrid management system, mediated by real-time communication protocols. The old operational paradigm based on (N–1) worst case dispatch, passive and forecast load demands, and controllable generator outputs has been replaced by a distributed model with tighter feedback between supply and demand to permit secure and efficient integration.

Microgrids have also gone virtual. The *virtual microgrid* (VMG) is a cyberspace concept that allows changeable segments of distribution networks to be managed as microgrids—a VMG can have a dynamic topology and can be configured electronically to facilitate certain operational objectives. As shown in Figure 4.6, a distribution network can be virtually partitioned into microgrids based on the physical feeder topologies, protection zones, or other partition and reconfiguration methods—the VMG scheme does not require a physical change in the connections of customers in a distribution network. The virtual network partitions are for the purpose of communication, information processing, control, and energy management. Unlike microgrids often operated as an attachment or extension to the distribution network, VMGs form the entire underlying layer of the distribution network. The whole distribution system has a hierarchical structure of at least two different levels/layers: the distribution grid level and the VMG level.
4.5.1.2 Microgrid management

A microgrid typically consists of interconnected loads and DERs that can operate in parallel with the grid or in an intentional island mode. A typical microgrid is composed of storage units; distributed generators, which are controllable units; renewable energy sources (RES), which are inherently intermittent; and controllable loads. In addition, a microgrid can purchase and sell power to and from its energy suppliers (see Figure 4.7). Several types of loads can be considered: critical loads (i.e., those with demand levels related to essential processes that must always be met); controllable loads (i.e., loads that can be reduced or shed in emergency situations); and shiftable loads that can be dispatched earlier or later to avoid penalties associated with peak demand or overloading of the grid.

In our 2030 scenario, microgrids are intelligent, robust, and secure energy delivery systems that incorporate 1) distributed energy, shortening the distance between power source and load and thereby reducing transmission losses; 2) novel fault protection schemes that cope with bidirectional power flow, unbalanced load, and distributed generators’ plug-and-play capabilities (i.e., a generating unit can be placed at any point of the electrical system without re-engineering the controls); 3) renewable energy sources, reducing carbon emissions; 4) energy storage, increasing power supply reliability and efficiency; and 5) an energy management and control system, which aims at increasing energy efficiency and reducing emissions.
Rooftops on every available surface have been efficiently used for solar power generation. Wind farms have been located at all economically viable locations, both offshore and onshore, and have been integrated with power and communications networks. Spatio-temporal cloud cover and wind patterns are predicted with sufficient accuracy over time horizons of interest, launching coordinated dispatch and control of neighborhood solar and wind farms and ensuring gridwide frequency and voltage stability.

High penetration of plug-in electric vehicles (PEV) has had a significant impact on distribution networks. In the past, PEVs were seen as increasing electricity demand and adding a significant burden on distribution networks. Today, they are both controllable loads and microgrid storage resources, used to smooth electricity demands over peak and off-peak loads.

With fossil fuel dependencies becoming virtually nonexistent, all organizational subsidies have gone towards building the microgrid infrastructure, which is now fully complete.

4.5.2 Control challenges for coordinated and hierarchical microgrids

4.5.2.1 Microgrid management: Coordinated control

Several challenges relate to the need for coordinated control to maintain power balance (active and reactive) and manage power flow and network voltage profiles. A further technological challenge for microgrid coordination is related to synchronization after changes in operating mode and in load/generation balance, especially with high penetration of renewable energy sources.
4.5.2.2  **Next-generation microgrid energy management system**

An outstanding challenge is the development of an EMS with advanced load controls, smart metering, generator monitoring, power conversion, and fault protection technologies to efficiently and safely integrate a diverse range of energy sources into a microgrid power bus. In addition, with the strong coupling between real and reactive power in microgrids, voltage and frequency control will need to be closely coupled.

4.5.2.3  **Control of hybrid energy storage systems**

Storage can prevent unstable operation during faults and maintain stability and power quality, especially in islanded mode. Both high energy and high power densities are required, but no one available technology is likely to satisfy both requirements. A hybrid energy storage system (HESS) with an appropriate control system could fulfill the need.

4.5.2.4  **Hierarchical architecture for distributed dispatch**

The distributed dispatch requires a two-way communication system between the energy dispatch center (grid operator) and the distributed microgrid dispatcher with coordination between distributed generators, storage, and consumers. This new paradigm uses real-time information obtained from Smart Grid devices as well as online market prices. Distributed dispatch with this mixed architecture will require novel approaches to multiple-agent optimization and self-organization, among other conceptual paradigms. With VMGs, another architectural decision space is opened: the optimal online, autonomous partitioning of the distribution network into VMGs.

The previous topics are elaborated in the next chapter of this report.

4.6  **Scenario 5: Transportation electrification**

4.6.1  **Flexible transportation energy management: A 2050 vision**

For both passenger and heavy haul freight, rail transportation energy needs are supplied entirely from a rich portfolio of electrical sources by the grid. Using widely distributed storage in new battery technology, flywheels, and fuel cells, nearly 100% of wind and solar energy renewables can be captured and stored at the wayside or onboard transportation assets until required. In new collaborative infrastructure among utilities, private freight railroads and newly revitalized public institutions worldwide (e.g., Amtrak in the U.S.), energy pricing and operations planning are coordinated to reduce peak demands and the attendant charges. The complex dynamic interactions involved in transportation scheduling for passenger and freight and the impact on electrical load are captured using new theories for hybrid and discrete systems applied to transportation-energy collaborative systems.

Decisions about whether to use and where to locate energy storage site (e.g., at the wayside or onboard some or all of the propulsion vehicles) are made with consideration of energy supply costs traded against needs to meet transportation constraints for goods and people. Dynamic feedback strategies using new generations of fast model-based control are employed with the ubiquitous communication infrastructure now available to optimally accommodate the stochastic variation expected with a high penetration of renewable energy sources. For example, a fully charged transportation vehicle can remain parked at a station to supply energy into the grid during a peak load.
situation and avoid excessive demand charges created by moving vehicles. Similarly, fleets of personal EVs parked at commuter stations can flexibly absorb or supply part of the load during the day. On locomotive and train-set rolling stock, the widespread elimination of step-down transformers, enabled by very high-voltage inverters using a new generation of 10 kV insulated gate bipolar transistors, allows efficient bidirectional power flow with the catenary, with nearly full recovery of braking energy while maintaining excellent power factor and low harmonic content in regenerated power. In heavy haul mining operations, advanced controls derived for transportation energy collaborative systems are now available to coordinate ship arrivals and departures with deliveries from mines so that just-in-time dynamic adjustments can be made to reduce waiting times in port by both ships and trains.

Benefits of these Smart Grid transportation energy collaboration systems derive for shippers (lower energy use per ton of goods carried), the public (lower transportation costs, higher reliability and availability for passenger transport), and utilities and independent third-party energy producers (reduced costs of electricity supply). Society benefits, too. By greatly reducing or eliminating fossil-fueled diesel-electric propulsion and substituting renewable-based all-electric propulsion, air-quality mandates are finally attained, and CO$_2$ emissions are minimized for the components attributable to rail transportation. Figure 4.8 depicts the combined electrical and transportation components of this realized vision.

*Figure 4.8 – Partition of transportation and grid-integrated system [Courtesy of General Electric © 2011]*
4.6.2 Control of rail transportation today

As suggested by Figure 4.9, railway electrification today is architected into an aging transmission infrastructure, typically from 25 kV single-phase 60 Hz or 50 Hz supplied from substations spaced 30 miles to 50 miles apart. Utilities might impose strict requirements on harmonics generated by the train load and otherwise limit the rate of load application or regeneration to assure that voltage limits are respected. A railroad could maintain hundreds of such substations within its territory. Trips for passengers and freight could span multiple railroad territories over regions like the U.S. northeast corridor from Washington D.C. to Boston, Massachusetts. Substations cost approximately $7 million each and the overhead catenaries cost on average $4 million per mile. A substation must provide upwards of 15 MVA for passenger and more for freight. Although in the U.S. the percentage of electric propulsion in heavy-haul is tiny, in Europe it is much larger, and both are growing. Today, there is virtually no onboard or at-the-wayside energy storage and limited regeneration because of voltage limits on the catenary (and because of the difficulty in coordinating capture of the braking power—instead, braking electric energy is dumped as heat). Costly step-down transformers on the locomotive or train set (roughly one-third of the locomotive cost) reduce the 25 kV to 1.5 kV to 3 kV for propulsion system operation. Coordination between railroad operators and utilities is typically loose and not real-time. Train scheduling for freight and passenger is usually centrally coordinated by private railroads (in the U.S.) or government entities (in the E.U. and most of the rest of the world) and incorporates considerable complexity so as to be able to respond adequately to customer demands over multiple time horizons. Rail dispatchers do not typically consider energy pricing or peak demands in their real-time operational decisions. Meets and passes for traffic within the network are adjusted from nominal schedules in real time to reflect dynamic conditions (early/late trains) and work crews on track (speed reductions). Train engineers are typically granted operational authority on a certain track and travel at or near line speed limits, stopping or slowing only where required by traffic ahead of them. When the utility grid is unable to meet demand during peak periods or following loss of generation from base plants or renewable transients, the trains simply slow or stop in the affected regions. Transit, light rail, and freight that rely on electrical power have great difficulty managing peak demand charges that arise during peak periods.

4.6.3 Realizing the vision—the role of control technology

4.6.3.1 System scope

Although our scenario emphasizes mainline rail transportation, its scope includes urban light rail and subway transit as key elements. Also included are EVs on surface streets (possibly hybrid with plug-in capability) for personal transportation and vehicle fleets with complex delivery routes in urban or intra-urban areas. All vehicles present electric loads that are complex functions of the type of propulsion system they possess, their energy efficiency, and dynamic driving profiles (speed/horsepower vs. distance, grade and curvature of the terrain). Electric loads can be further complicated by the presence of on-vehicle storage such as batteries or flywheels and how stored energy is used or recovered during braking, while in operation, and when idle. For rail vehicles on a catenary supply system, the load is affected by whether the mechanical propulsion requirements are met from the catenary, supplied by storage, or both. Further, even parked vehicles can contribute to load when charging on-board storage. Bidirectional inverters allow power flow back into the catenary from storage, braking, or as required by needs of the grid to meet demand elsewhere in the network, (e.g., to compensate for renewable intermittency such as with wind or solar).
4.6.3.2 Grid-transportation integration and control

The key control problems for which solutions are sought include concurrent solutions to the following problems, which can be viewed over multiple horizons of interest (hours to days or longer):

1. **Trip planning for trains/vehicles in the system.** Trip planning must factor in origins, destinations, and intermediate stops to pick up and discharge people, goods, or both, subject to available power (locomotives, train sets, EVs) and rolling stock. Routes and timing of trips must be selected to minimize various energy metrics (e.g., total expended energy, kWh/km) and energy cost (reflecting pricing structures with demand charges). Trip planning must also be sensitive to dynamically varying route availability and constraints along the route.

2. **Grid planning including the transportation network, available generation sources, nontransportation loads, and available storage.** This planning includes decisions about unit commitments (what generation sources and controllable loads to use and when) and assignments (how much power each source/load should produce or use when it is online). Architectures might be increasingly heterogeneous, including microgrids and adjacent distribution/transmission systems with high penetration of renewables.

3. **Real-time update to the combined plans.** The planning solutions derived for the problems previously are based on forecasts and expectations. During system operation, deviations will
arise, such as power imbalances and unpredicted renewable shortfalls on the electrical side and schedule disruptions for trains. Based on sensor measurements, and updated models and forecasts, trip and grid plans must be updated dynamically and in closed loop.

None of these problems are new, but they are currently addressed in isolation. The research need is for an integrated, dynamic approach. Railway and grid operators will need to collaborate, both for planning and during transportation system operation. Such a holistic approach would have numerous benefits: 1) concurrent starts in the transit system could be avoided to minimize peak demand charges for electricity, 2) on-board storage could be exploited to back-feed the network from a braking or idle train to fill in demand gaps in the grid, and 3) schedules could be developed that are more robust to grid problems.

### 4.7 Scenario 6: Distribution automation

#### 4.7.1 Distribution network systems: Then and now

Future distribution systems will be active and adaptive networks that differ from existing systems in four important aspects. First, future distribution systems will have massive penetration of distributed generation integrated in both medium-voltage (MV) and low-voltage (LV) grids. Distributed generation will be pooled as virtual power plants, and their aggregated power will be dispatched automatically. As a result, power flow will become bidirectional, with appropriately designed real-time operation and protection schemes. Second, microprocessor-based relays, also called intelligent electronic devices (IEDs), will be installed throughout distribution systems to integrate multiple functions (such as metering, protection, automation, control, and digital fault recording) and to efficiently manage power system services. Third, smart distribution grids will have hierarchical communication networks as shown in Figure 4.10: wide-area networks (WAN), neighborhood-area networks (NAN), and user-area networks (UAN). A WAN aggregates MV grid data and long-range...
communication by connecting devices such as substations, voltage regulators, line switches, capacitor banks, and transformers; its purposes are to enable substation automation, distribution automation, SCADA, and fault diagnostics and recovery. A NAN facilitates the formation, control, and optimization of microgrids and their virtual power plants. A UAN enables customers to actively manage their load, storage, and generation devices according to real-time pricing and operational conditions. Fourth, smart distribution systems will use distributed sensing, estimation, optimization, and control algorithms to allow massive penetration of distributed renewables, to automate system operation for improved reliability, to make the system self-healing in the event of faults and natural disasters, to ensure security and safety, and to implement new business models for better efficiency and economic and social benefits.

Our envisioned future can be contrasted with today’s practice. As shown in Figure 4.11, a typical distribution system includes distribution substations, primary distribution feeders, distribution transformers, secondary circuits, and appropriate protective and control devices. It delivers electricity from high-voltage (HV) utility transmission systems to end users in two stages: the primary distribution portion is designed to operate at medium voltages (between 2.4 kV to 35 kV in the U.S.), and the secondary distribution portion has low voltages (between 100 V and 600 V). Distribution transformers are used to step down the voltage, circuit breakers are employed to tie a distribution system together, and devices such as on-load tap changers (OLTC), switchable capacitances (CAP), and static voltage compensator (SVC) are used to provide reactive power compensation and maintain voltage stability.

![Figure 4.11 – Distribution network (modified from Mbizon [2])](image-url)
At present, most MV grids have a radial topology; their operation and protection schemes are simple and do not support directional discrimination. There are very few intelligent devices (beyond radio-controlled relays and OLTCs). Distribution network operations are planned (open-loop) because changes in demand are relatively slow and statistically predictable, and voltages are coarsely regulated (the typical range is 5%). There is little measurement data available in real-time to determine the operational state of distribution systems or their equipment.

4.7.2 Technical challenges and potential solutions

Several technical challenges will need to be addressed to make the leap from the present state of distribution automation to the vision outlined by the scenario. Below we briefly note a few areas of particular need and opportunity. See Chapter 5 for details.

4.7.2.1 Design and implementation of local communication networks for distribution networks

To maximize the use of distributed generation resources while scheduling and meeting dynamic demand and maintaining grid stability, sensing, optimization, and control (SOC) algorithms must be designed in concert with an underlying real-time communication and networking infrastructure. The communication network must meet the real-time demands of Smart Grid SOC across the power/communication network hierarchy. At the same time, algorithm synthesis must be informed by communication network properties, including bandwidth, delay, throughput, and redundancy.

4.7.2.2 Heterogeneity and multiple timescales

In addition to distributed generators, distribution systems contain heterogeneous devices including power electronics and storage elements. These devices have different response speeds in voltage regulation: from minutes and longer for OLTCs and capacitor banks, to milliseconds for FACTS devices. Accordingly, their actions need to be coordinated and adapted to account for these different timescales. For instance, transformers with OLTC should be controlled mainly for steady-state voltage regulation and with consideration of varying distributed generation capacity, and distributed generators and FACTS devices should be controlled to avoid voltage flicker and compensate for voltage sags.

4.7.2.3 Coordination of demand, storage and generation

With distribution systems containing vast amounts of electricity production, storage, and communications, aggregated distribution system resources must be coordinated and scheduled to manage power flow into (or perhaps even out of) distribution substations. A specific challenge in this context is to gain an understanding of the spatio-temporal variations and correlations in power flows on distribution circuits resulting from massive spatially distributed photovoltaic generation capacity behind customer meters. Constraints and uncertainty must be considered, as well as the interaction between these issues and voltage regulation objectives.

4.7.2.4 Cooperative control of distributed generation (both active and reactive)

With high distributed generation penetration levels, heterogeneous DERs, and a broad variety of demand-responsive loads, the current practice of solving for optimal power flow is neither feasible nor economical. Distributed control concepts such as self-organization, cooperative control, and virtual leader-follower architectures could provide the needed game-changing alternative.
4.7.2.5 Optimization of network operation with game theory

We must not only develop optimal distributed control algorithms for networked power flows, but must also establish criteria for optimality—balancing the interests of consumers, centralized producers, distributors, and society at large. Interaction among these entities and the main grid can be formulated as a game-type optimization problem, with distributed algorithms enabling optimal and autonomous dispatch of aggregated distributed generators and customers developing individualized optimal strategies.

4.7.2.6 Distributed state estimation and verification

Because of the expansive nature of distribution networks, it is not economically feasible to make all IEDs and their communication secure or to store all of the data at a secure central location. Distributed state estimation methodologies can be developed, using the properties of physical distribution networks, cloud computing, and big data innovations to ensure safe islanding operation and other requirements.

4.8 Scenario 7: AC-DC transmission systems

4.8.1 A control-centric transmission grid vision

The high-voltage transmission grid is now heavily power-electronics based, and numerous long-distance and back-to-back direct current (DC) transmission lines provide fully controllable point-to-point power delivery (see Figure 4.12). This DC grid is overlaid on the existing high-voltage AC transmission grid, which continues to serve loads within a control region. Some of the DC systems have been converted from previous AC systems, while others have been constructed anew. The new DC grid has proven effective at linking remote renewable resources to urban centers and in bypassing power transmission bottlenecks. As a result, renewable energy resources (e.g., hydro, wind, and solar) have displaced fossil units. Land-based wind resources, for example, are most abundant on mountain ridges and on vast areas of flat land primarily used for agriculture. These regions tend to be sparsely populated and their commensurately weak transmission systems in the past precluded their extensive use for renewable generation. Advances in high-voltage DC transmission have changed the picture—for distances of about 1000 km or greater, modern high-voltage DC systems are much more economical and efficient, and can be loaded up to their full ratings with few stability problems. The benefits of DC systems to offshore wind resources (which are much more consistent generators than land-based resources) are even more significant—the break-even point of undersea cable AC versus DC systems has dropped to about 50 km.

Storage devices are widely used to reduce the variability of wind and solar resources and during peak load periods. Storage devices come in a variety of forms, including single-purpose equipment such as a flywheel facility and multipurpose equipment such as the battery packs in electric vehicles.

In addition to its use for integrating large-scale renewable generation, DC transmission also supplements capacity-constrained interfaces, which can exist between two operating regions or between generators and loads in the same operating region. Sometimes these transmission systems extend over a relatively short distance, possibly in the same substation area—hence the name back-to-back DC.
The AC transmission grid is also supplemented by power electronics-based FACTS controllers using thyristor or voltage-sourced converter technology. Series type controllers—such as thyristor-controlled series compensators (TCSC), static series synchronous compensators (SSSC), and other newly invented, more powerful controllers—are used to adjust the power flow in critical transfer paths. Shunt type controllers—such as static VAR compensators (SVC), static synchronous compensators (STATCOM), and other controllers unknown in 2010—are used to control the voltages in the AC power grid. These series and shunt controllers are critical in 1) Supporting DC power transmission systems, especially those injecting power into the so-called weak AC systems, and 2) Dealing with the variability of power injections from renewable resources. In both situations, they provide proper dynamic reactive power support when a rapid readjustment of power flow due to sudden wind drop-off or stormy conditions occurs.

This integration of AC and DC transmission is based on sensing and control. For sensing, the use of monitoring devices for measuring voltage and current phasors, both single-phase and three-phase, synchronized with a common clock signal, is now commonplace. Operators have access to the monitored data in less than a second and automatic control systems receive sensed information in less than 100 milliseconds.
Given any measurable disturbance, such as a line trip, generator trip, or a fault, operators can now immediately see and replay the disturbance. Energy management systems advise operators as to the severity of disturbances and the vulnerability (such as stability margins) of current operating states. Fast control actions, such as changing the set points of FACTS controllers and feedback regulation of bus voltages, are performed automatically. The EMS also performs predictive simulations and advises operators if any manual control actions from a choice of options will be needed in the longer term.

In summary, revolutionary advances have happened in the flexibility and controllability of the transmission grid. The monitoring system is vastly improved and can make maximum use of the controllability to ensure optimal and reliable operations.

4.8.2 Current state-of-the-art in transmission systems and control

Most current transmission systems are AC-based. In some regions, transmission bottlenecks are common during high-load periods, resulting in high energy prices. Uncontrolled loop flows occur in some areas; that is, flows that should go directly from Station A to Station B instead go through Station C, increasing the transmission distance and hence power losses. In addition, undesired loop flows might overload transfer paths in a neighboring system.

Renewable energy penetration, not including hydro, is still quite low. Most large renewable energy installation involves wind farms of a large collection of wind turbines. Most of them are located next to existing substation or transmission lines, using the spare capacity on these transmission systems. However, such desirable locations (with minimum new transmission needs) are nearly exhausted. Further wind farm investment could require substantially more transmission infrastructure investments. Solar PV installations are relatively modest in number and size and are mostly behind the meters, thus not directly monitored by the grid operator.

The EMS used by power grid operators is relatively low bandwidth, with data updates every five seconds or more. The data is not sampled synchronously or simultaneously, and the timeliness of the data is not monitored, that is, the value of a variable might be stale. Subsecond transient behaviors are not observed by operators. The origin and causes of disturbances might not be known until long afterwards and the health or viability of neighboring power control regions is not normally known. Operators cannot prevent cascading blackouts due to contingencies from neighboring regions. The lack of a trustworthy wide-area monitoring system with a common clock and high speed measurements inhibits the implementation of advanced control and protection applications.

4.8.3 R&D challenges and opportunities for control science and engineering

The implementation of the future integrated AC-DC transmission grid requires both equipment technology (such as power devices and converter technologies) and control system design. We will focus here mostly on the control side. The discussion on the equipment side will be mostly for control system implementation. Once again, details on these transmission control research areas are provided in Chapter 5.

4.8.3.1 Control functionalities and architecture

One of the first tasks is to develop a control architecture based on additional measurements and controllability. This advanced control architecture will use the synchronized measurements platform
provided by wide-area measurement systems (WAMS). The new control architecture will be wider in scope and deeper in function. To be comprehensive, it requires surveying all of the control functions currently used and rethinking their applicability and implementation in the future power system. On the other hand, after a general control architecture has been developed, new control functions could be implemented.

4.8.3.2 **Closed-loop control under large disturbances**

Today’s power systems have limited capabilities to handle large disturbances such as can result from the loss of a large amount of generation or an important transmission line outage. We need to change the conventional control paradigm from event-response to closed-loop control based on system response, but the fast dynamics and large-scale nature of power systems complicate matters considerably.

4.8.3.3 **Coordination with uncontrolled variable generation**

One of the primary impacts of uncontrolled variable renewable generation resources on a power grid is the need for reactive power support. Transmission system control is critical when the shortfall of renewable energy in a particular region must be compensated by remote generation. Such reactive power support can be dynamically provided by FACTS. FACTS, however, are expensive—a research challenge is to develop low-cost reactive power support for increasing penetration of renewable generation.

4.8.3.4 **Network control**

In a power system with multiple synchronized measurement devices, a communication network infrastructure is necessary to provide reliable connections between the measurement devices and the controllers. Network control will be needed to keep delays and errors minimal when some communication links are down, and control algorithms that are robust to such disruptions will be needed.

4.8.3.5 **Supervisory monitoring and control**

Today’s power systems have limited capabilities to respond to rapidly changing network topologies during off-nominal system behavior, specifically before and during contingencies and during recovery from a contingency. Multiple objectives need to be achieved during these off-nominal system modes based on the level of the contingency and requirements and specifications from system operators. Partial observation of the network and neighboring regions because of physical constraints, economics, and policies adds another layer of complexity to the problem, requiring stochastic models. Automated switching and operation of devices during off-nominal behavior are needed to reduce the impact of contingencies, improve recovery times, and increase the lifetimes of devices on the network. Recent advances in the supervisory control of partially observed discrete-event systems that incorporate hybrid network models could provide a solution.
4.9 Scenario 8: Renewable generation

4.9.1 The future: Wind and solar generation support the grid

It is 2030, and wind and solar power now provide over a third of the world’s electrical energy needs, several-fold more than in 2010 when the penetration percentage for each was in the low single digits. In some countries, the average penetration of wind energy alone now exceeds 30%, with instantaneous penetrations reaching 100% at times. In 2010, both wind and solar energy were already growing quite rapidly and benefiting from developments in control systems theory and technology. For example, control systems were already playing a prominent role in the design and deployment of wind turbines. The goals of traditional wind turbine control systems were to maximize energy production while protecting the wind turbine components. As more wind generation was progressively installed, there was an increasing interest in wind turbines actively controlling their power output in order to meet power set points and to participate in frequency regulation for the utility grid.

Since 2015, regulations have required that 1) new wind farms provide an inertial response and primary frequency response when grid frequency deviates from the normal operating point and (2) wind farms meet a power set point (based upon forecasting) provided by the transmission system operator (TSO) at a specified rate of change. These requirements comprise active power control (APC) services—the purposeful control of the real power output of a wind turbine or wind farm in order to assist in balancing total power generated on the grid with total power consumed. Wind turbines can synthesize APC commands through control of their generator torque and blade pitch commands. In fact, the APC services provided by a wind turbine can be more flexible than those provided by conventional generators. Wind turbines and wind farms now regularly provide response in all of the inertial, primary, and secondary timescales—from subseconds to several minutes. All wind farms constructed since 2015 have been outfitted with progressively more sophisticated active power control systems capable of responding to TSO power set-point commands and automatically responding to fluctuations in grid frequency.

APC has allowed wind power to provide important ancillary services to the electrical grid and assist in maintaining an acceptable grid frequency. Although it has been demonstrated that wind turbines are more effective at providing APC services than traditional power plants, ongoing research is focused on determining the upper bound of the frequency regulation capability of wind turbines.

The interconnection of a wind farm controller with the utility grid, TSO, and individual turbines can be seen in Figure 4.13. The individual turbine can follow the power reference from the wind farm controller by altering the standard generator torque and blade pitch feedback loops. As research and wind farm implementations have demonstrated since 2010, increasing the power regulation performance of a wind turbine control system can be complicated due to a number of factors, including coupling with existing control loops, a desire to limit actuator usage and structural loading, and wind variability.

In summary, the intermittency of wind is no longer considered the major obstacle to large-scale penetration of wind power that it once was, and the greater capability of wind farms to provide inertial/primary and secondary frequency response services than conventional generators has turned out to be a tremendous benefit for the grid.
Figure 4.13 – Control and power flows for active power control commands. The wind farm controller can measure the frequency of the utility grid and receive an automatic generation control power command signal from the grid operator, and in turn produce a power reference for each turbine in the wind farm. [Figure courtesy of J. P. Aho of the University of Colorado-Boulder.]

Significant advances have been made for solar power as well. Both concentrated solar plants (CSP) and PV deployments are widespread. The former are utility scale, and the latter include PV farms as well as vast arrays of rooftop units—in many neighborhoods worldwide the majority of homes feature these units. Storage integration has been a particular success story with CSP, with thermal storage enabling efficient temporal decoupling of insolation and electricity generation.

Research in power markets has also opened pathways for implementing an ancillary market for power regulation capabilities. With wind farm and solar plant capabilities demonstrated, and the need of the utility grid for active power control services, this type of market rapidly increased the economic viability of renewable energy resources, leading to the high penetration levels today in 2030.

4.9.2 Research challenges and opportunities for control technology

A number of research topics must be investigated in depth before the vision outlined previously can be realized. We briefly note several important topics here; further details on selected topics are provided in Chapter 5.

4.9.2.1 Forecasting and prediction

The main drawback of both solar and wind energy is their unpredictable intermittence. A key need to address this challenge is forecasting. Predictions of renewable generation, with uncertainties quantified, are needed at timescales ranging from minutes (although at the single wind turbine level, even subsecond predictions are of interest) to several days. One forecasting approach cannot serve all needs—different approaches are best suited for different renewable-generation sources, for different prediction horizons, and for different control and planning functions.
4.9.2.2 Storage integration—electrical and thermal

Massive energy storage has the potential to mitigate the intermittency and unpredictability of renewable energy resources. Storage technologies are under intense research, including batteries, pumped water, supercapacitors, compressed air, flywheels, superconducting magnetic energy storage, and hydrogen (fuel cells). Solar thermal power plants provide additional storage options. Molten salt devices are especially promising for high-temperature thermal storage for later use in electricity generation. Such thermal reservoirs can store relatively high amounts of energy for as long as 6 to 8 hours.

The integration of storage with renewables presents numerous opportunities for research (e.g., the definition of models and optimization formulations that can result in strategies for charging and discharging).

4.9.2.3 Coordinated control of renewable generation

The geographic diversity of solar and wind power can smooth the impact of weather variations. Grid controllers should thus handle renewable generation on a wide-area basis. Effective integration will require coordinated control with bidirectional SCADA communication, remote ability to control (turn on and off) or curtail load and generation, power factor control, and remote diagnostics and prognostics. Furthermore, a utility operator with thousands of rooftop PV systems in a service area would not be able to take full advantage of them unless the systems could be modified as an aggregate. Controllers with capacity for adapting to the formation, and disintegration, of dynamic coalitions of producers are needed.

In wind farms, the need for coordination extends to intrafarm operations. Wake effects can reduce generation in downstream turbines to as little as 10% of the leader turbine. These effects can be modeled and individual turbine controllers can be coordinated so that the overall wind farm efficiency and reliability are optimized. The layout of new wind farms could also be better optimized to account for such wake effects, which not only affect power production but can also result in higher structural loads in downstream turbines. Inertial and primary control can also be implemented at the wind farm level. Methods for intelligent, distributed response of entire wind farms to grid-frequency disturbances could significantly reduce such deviations and improve recovery speed.

4.9.2.4 Control of wind turbines

Numerous technologies will need to be developed to meet performance demands set forth by TSOs and allow for control of active power output and provision of ancillary services. With wind turbines, inertial and primary response and power set points could be achieved, at the different timescales involved, with pitch control and generator torque control. Wind turbines can also be used to provide implicit power reserves by operating at higher-than-optimal rotor speeds—during an underfrequency event the controller can increase the generator torque to slow the turbine down to the optimal speed. However, trade-offs between aggressive frequency response and induced structural load must be carefully analyzed and managed.

4.9.2.5 Control of photovoltaic systems

Technical regulations require generation plants to maintain the voltage level and also to contribute to the reactive power balance of the grid. For PV systems, these requirements suggest improvements in inverters and their control function. Control systems for inverters will be needed to change the power factor and the delivered active power in response to external demands from utilities and based on the
grid frequency. At a distributed generation level, PV controllers will also be required to maintain system operation during failures in the grid—maintaining PV operation through transient faults with ride-through capability.

### 4.9.2.6 Renewable energy systems optimization and control

The operation of renewable energy systems must be optimized with several criteria and constraints in mind—technical, financial, and environmental. Methods for system planning and development must cope with the uncertainties and stochastic aspects of renewable generation. Approaches capable of handling such complexities—for example, advanced stochastic programming—must be developed for system planning and control.

The real problem, of course, is more complex yet—optimization of renewable energy systems cannot be a stand-alone solution; coordination, or co-optimization, with storage operation planning and demand management, among other functions, will be needed.

### 4.10 Conclusions

As exemplified in the previous scenarios, control technologies can play a crucial role in achieving the broad societal drivers for the Smart Grid: massive penetration of renewable generation, transportation electrification, reliability of supply under all conditions, consumer engagement and empowerment, and cost efficiencies for all stakeholders. It is unsurprising, then, that our scenarios are not limited to a subset of Smart Grid domains or systems, but rather span the full design space. The relevance and importance of control extends across bulk and distributed generation, transmission and distribution networks, residential, commercial, and industrial facilities, and power markets and regulators. Novel control-related insights also suggest that the architecture and partitioning of today’s power system can be radically rethought.

We emphasize, though, that these scenarios are not business-as-usual projections. Their fruition is contingent upon targeted and intensive research and development in control science and engineering. Fortunately, the strong fundamentals and rigor of the field provide an ideal foundation on which to design and construct revolutionary Smart Grid infrastructures. We also note that the presented scenarios are interdependent, so that significant synergies, including common research opportunities, abound. The next chapter of the report discusses the research topics highlighted in the previous scenarios in more detail.

### 4.11 Citations


5.1 Introduction

By the year 2050, we envision a dramatically different electric grid than what exists today. In Chapter 3, various drivers for a new vision for the electric grid were delineated. This chapter also emphasized the crucial importance of control for realizing this vision. In Chapter 4, different futuristic scenarios of the grid were delineated, including realizations of an efficient market, idealized grid-pervasive
demand response, rapid real-time endpoint control, smart periphery with a fully coordinated network of microgrids, synergistic electrified transportation, green and automated distribution systems, and efficient AC-DC transmission networks. In this chapter, we outline the research breakthroughs that need to occur to overcome the daunting and substantive technical problems posed by these scenarios.

It is not an exaggeration to claim that every system and process in the future grid—from operation planning to unit control, from generation to end-user consumption, with dynamics ranging from years to milliseconds—will be influenced by some aspect of control. These different facets of the grid, with the ways in which control can offer fundamental changes and improvements within each of these areas, are described in the following sections. We classify these different loci of control into four categories. The first of these categories, addressed in Section 5.2, concerns innovations in the traditional subsystems of generation, transmission, and distribution. In the second category, addressed in Section 5.3, we present emerging roles pertaining to areas where the grid has opened for a control-oriented perspective and solution. These encompass market mechanisms, demand response, storage and transportation, microgrids, and virtual power plants and aggregators. The third category, discussed in Section 5.4, presents a control point of view across the entire grid, the implementation of which necessitates new approaches and paradigms. These include topics such as energy efficiency, cyber security, thermal storage, and interplay between communication and control. In Section 5.5, we outline a fourth and final category that includes possible game changers that could result in a radical rearchitecture of the grid, leading to a grid with a huge number of active endpoints, collectively achieving the desired goals of power delivery and a self-healing grid that responds, corrects, and restores power delivery following any anomaly. In all four sections, the conceptual problem, the control-related challenges, the risks, the supporting technologies, and the possible impact are outlined. Section 5.6 presents emerging themes of control that the evolving grid has ushered in. The entire grid can be viewed, essentially, as a system of distributed systems, where elements of estimation, regulation, optimization, network science, and many other facets of decision making have to be carefully crafted, analyzed, and refined. The fact that the grid is a socio-economic, cyber-physical system opens the door of control to entirely new disciplines of sociology, economics, and psychology. All of these elements are touched on in Section 5.6.

5.2 Loci of control: Innovations in current power systems

Generation, transmission, and distribution are major components of current power systems that face significant challenges with the ushering in of Smart Grid. We discuss control research needs in these areas in this section.

5.2.1 Renewable energy generation

Research challenges abound in this topic, a major driver of change in the power grid. We focus on the main challenges in this area of intense research that are control centric and will serve as important building blocks for many other emerging areas of research activity.

5.2.1.1 Forecasting and prediction

Decreasing the degree of uncertainty in predicting both wind and solar radiation is a fundamental issue for their effective integration into the grid, particularly at high penetration levels. There are very accurate models for predicting the solar radiation variability due to the daily movement of the sun in
a perfectly clear sky situation. The variability due to weather conditions is more difficult to predict and requires an online solution.

Short-term forecasting of wind can use numerical prediction algorithms based upon atmospheric models and continuously updated based upon point measurements of wind velocity, temperature, humidity, pressure, etc. Current numerical codes are highly computationally complex at the required spatial resolutions (tens of meters both horizontally and vertically across a wind farm that might span hundreds of square kilometers with wind turbines having 100-meter rotor diameters) needed for accurate wind farm power predictions.

Short-term forecasting of solar radiation can be based on the analysis of satellite images, ground-based sensors, cameras, and solar plant output from other locations. Solar radiation is affected by the filtering effect of clouds. Precise models of their dynamics, as well as pollution forecasts, are needed. Short-term predictions of the effect of clouds are mainly due to the movement of the clouds, which can be determined by image processing or other techniques.

Longer term solar and wind forecasts will be based on weather forecast and model identification and estimation. Methods to aggregate heterogeneous data coming from many different locations will be needed to generate more accurate predictions.

The wind and solar forecasts can be used alongside electrical load forecasts by grid operators to schedule the power production of conventional generators to mitigate the impact of weather-related uncertainty on the grid operation. Better predictions in the long and short-term forecasts can improve the capability of wind and solar to bid into the day-ahead and 15-minute-ahead power markets more confidently, and appear more like conventional generators in these markets. Improvements in the short-term forecasts will allow grid operators to better control the balance of power generation and load, which improves grid reliability by regulating the grid frequency. Furthermore, recent advancements in the control of wind turbines and solar photovoltaics (PV) has enabled them to control their power production by capturing a fraction of the available resources, which allows grid operators to schedule their power production and also enables them to participate in frequency regulation services provided that the short-term forecasts are sufficiently accurate.

5.2.1.2 Wind energy

Wind turbines and wind farms are now being recognized as having the potential to meet demanding grid stabilizing requirements set by transmission system operators (see [1, 17, 21, 39, 56, 64, 68, 70, 101] and references therein). Recent grid code requirements have spurred the development of wind turbine active power control (APC) systems, which allow wind turbines and wind farms to participate in grid frequency regulation and provide frequency response to sudden changes in grid frequency. The ability of wind turbines to provide APC services allows them to follow forecast-based power production schedules and allows them to participate in secondary frequency control, or automatic generation control (AGC). The AGC commands are generated from a highly damped proportional-integral (PI) controller to regulate grid frequency and are used to control the power output of participating power plants. To fully participate in AGC, a power plant must be able to increase or decrease its power output to follow the AGC power commands as the grid frequency decreases or increases, respectively. Alternately, these APC systems must be capable of responding to more rapid frequency fluctuations by varying their power output, both of which have historically only been met by conventional generation sources. These APC systems can be designed to provide services over various timescales, from rapid inertial and primary frequency responses to the smoother tracking of the grid load to regulate grid frequency. A number of research topics must be investigated in depth to
to better understand the full capabilities of wind turbine and wind farm APC. The following topics are examples:

1. **Automatic generation control.** If a wind turbine is extracting the maximum energy from the wind stream, it can only participate in AGC when the grid frequency is too high and a decrease in power output is required. A wind plant that is derated or following a power production schedule might be operating suboptimally and might be able to extract additional power from the wind stream, allowing the plant to participate in AGC when the grid frequency is too low, as well. Accurate short-term forecasts will allow for the available wind power to be calculated and could be used to determine the AGC participation factor for the wind farm, provided that the AGC participation factors are rapidly updated to reflect changing wind conditions.

   One approach for maintaining an active power set point with wind turbines is to rely on pitch control over the relatively slower secondary response timescales. Pitching the turbine blades away from the optimal power pitch angle will reduce the aerodynamic power captured by the rotor and effectively derate the turbine. Another approach for derating a wind turbine is to operate at a higher than optimal tip-speed ratio (or rotor speed) to maintain a reserve of available wind power. The latter approach has the advantage of storing additional inertial energy in the rotor, which is useful for providing inertial frequency response as discussed later, but this approach can only be used when operating below the turbine’s rated speed.

2. **Primary and inertial frequency response.** Another important aspect of maintaining grid reliability is the capability of generators to respond automatically to more rapid fluctuations in the grid frequency. These rapid fluctuations could be induced by a sudden change in generation or load, such as a generator dropping offline. Frequency response is typically only provided by conventional generators and is divided into two components: inertial response and primary response. Conventional synchronous generators inherently provide inertial response, as they will either absorb or inject inertial energy as they speed up or slow down due to the imbalance between generation and load, therefore causing the grid frequency to vary. The primary frequency response provided by conventional generators can be characterized by a droop curve. Droop curves typically relate fluctuations in grid frequency to a corresponding change in power from the governor of a conventional synchronous generator. Wind turbines do not inherently provide primary or inertial frequency responses because their power electronics provide a buffer between their generators and the grid, but such responses can be induced synthetically by the turbine control systems.

Wind turbines can derate their power output by pitching their blades to shed aerodynamic power or by operating at higher than optimal tip-speed ratios, as previously mentioned. A de-rated turbine can provide frequency response to both overfrequency and underfrequency events, whereas a turbine extracting maximum energy from the wind can respond well to overfrequency events but can only increase power output by extracting inertial energy from the rotor, which must be followed by a lower power recovery period. The trade-offs between aggressive frequency response and induced structural loads on wind turbines need to be analyzed carefully. Initial research shows the potential that grid support can be achieved with only small increases in structural loading on wind turbines and thus without significantly increasing fatigue damage and operations and maintenance costs [17].

One method of providing primary frequency response with wind turbines is to rely on pitch control to track the lower frequency components of the primary frequency response while the higher frequency components of the primary response and the faster timescale (subsecond) inertial response can be
performed through the generator torque control to emulate the built-in response of a conventional generator. Wind turbines can in principle provide more inertial frequency regulation than conventional generators per unit of spinning inertia, because of the wide range of generator operating speeds and the speed at which the power electronics can actuate the torque command signal.

Operating the turbine at higher than optimal tip-speed ratios (or rotor speeds) to maintain a reserve of available wind power has some advantages. During an underfrequency event—indicative of a generation shortfall—the controller can increase the generator torque to extract inertia from the turbine, causing the turbine to slow down to the optimal tip-speed ratio. These controllers could therefore implement inertial and primary response by producing a higher power output when under-frequency events are detected. Pitch control can be used to derate the turbine and further add to the primary response. Consideration of stability issues arising from the interaction between the torque and pitch control loops must be analyzed.

Frequency control using droop curve concepts with wind turbine control systems has recently been investigated [1, 17, 21, 69, 100]. Augmenting a wind turbine control system designed to provide AGC response with a droop curve can allow the wind turbine to also participate in primary frequency response without requiring additional control loops. A droop curve enables the APC system to automatically respond to changes in grid frequency in addition to active power set points requested by the grid operator. Using a droop curve to augment the existing APC controller simply modifies the power reference signal, allowing power reference to still be the only input into the control system.

A wind turbine droop curve is implemented synthetically and serves only to generate a power reference into the APC system. This droop curve differs from a traditional synchronous generator, where the droop curve characterizes the physical response of the governor. Therefore, for wind turbines, droop curve characteristics can be time-varying and dynamically changed online and can also be asymmetric (e.g., more aggressive slope for overfrequency events than underfrequency events). Dynamically shaping the droop curve has been shown in simulation [17] to allow for more aggressive response in reaction to large rates of change of frequency, effectively adding extra inertial response, without inducing excessive loads on the turbine components. Figure 5.1 shows a simulation of a grid response under three different scenarios when 5% of the generating capacity suddenly goes offline. When the wind farm (15% of the grid) is operating with its normal baseline control system that does not provide APC services, the frequency response is worse than the no-wind scenario, due to the reduced amount of conventional generation in the wind-baseline scenario that can provide power regulation services. However, compared to both the no-wind and wind-baseline cases, using an APC controller with a dynamic droop curve results in the frequency decline being arrested earlier and the deviation being less severe.

In developing APC controllers for wind turbines and wind farms, the trade-offs between aggressive frequency response and induced structural loads on wind turbines need to be analyzed carefully. Several studies have simulated APC at the grid level [21, 64, 68, 70, 101], one study has simulated APC at the turbine level to analyze loads [56], and one study has recently simulated and analyzed APC at both the grid and turbine levels simultaneously [17]. This latter study demonstrates that frequency regulation can be achieved using both static and dynamic droop curves, with aggressive frequency response generally coming at the cost of increased structural loads on the turbine. Dynamic droop curves can potentially mitigate this problem, with more aggressive frequency response incurring only marginal increases in structural loads.
Figure 5.1 – Simulation results showing the capability of wind farms to provide APC services for the utility grid. At 1000 seconds, 5% of generating capacity goes offline. The system response with all conventional generation (no wind) is compared to the cases when there are wind farms on the grid at 15% penetration (i) with a baseline control system (wind baseline) where wind does not provide APC services or (ii) with an APC system (wind APC) that uses a dynamic droop curve [10]. (Figure courtesy of A. D. Buckspan of the University of Colorado-Boulder)

Other research topics under this heading are enumerated here:

- Optimal participation by wind farms over all regulation phases
- Development of strategies to balance aggressive power control against increased actuator usage and structural loads

5.2.1.3 Solar energy

Three distinctive control levels occur in most solar energy plants: 1) the control of the solar collectors, 2) the control of the collected energy main variables, and 3) the overall control of the process [18]. These levels are explained as follows:

1. To control the collectors, the sun movement is tracked in such a way that the maximum solar energy is collected at any time. The controller computes the sun vector, which depends on the position of the collector and the date and time of the day. Feedback mechanisms are used for small corrections. In the case of solar troughs, simple optical devices are used. In the case of solar towers, the individual energy contribution of each of the heliostats to the flux received by the central receiver cannot be measured. Image processing methods are used to calibrate each of the heliostats and correct the heliostats pointing errors [14]. Tracking mechanisms in some solar PV panels use a fine feature aimed at maximizing the energy received [79].
2. The main controlled variable of PV panel is the electrical current. PV plant inverters use a maximum power point tracking (MPPT) mechanism aimed at generating the maximum power, which depends on the load and the solar conditions. Many solar PV plants use a single MPPT for the entire array of panels, and the same current is used for all the panels. Because the panels may have different current-voltage (I-V) curves, due to different manufacturing tolerances or different shading, some panels will be operating below the optimal operating point. Solutions based on individual inverters seeking MPPT for each of the panels are now being used. The most common maximum seeking methods used are the perturb-and-observe method [98] and the incremental-conductance method [43].

Advanced control strategies have been used for controlling solar trough plants (see [18, 19] and references therein). The main problems are that the primary energy source—solar radiation—cannot be manipulated as with other power plants. Furthermore, the solar radiation can be a source of strong disturbances for the control system, because not only does it change slowly throughout the day, but also rapidly due to clouds. The plants also exhibit nonlinearities and variable dead time.

Algorithms for obtaining a uniform flux distribution in solar towers have been used in experimental plants [46]. The algorithms use a set of focal points, which are moved in order to get a minimal difference between the highest and lowest temperature measured at different points in the receiver.

3. The overall control of the plants consists of determining the main operating variables throughout the day. This control not only involves determining the operating temperatures and pressures for the heat transfer fluids, but also determining the power to be delivered and stored when the plants have a storing capability, as is the case with most thermal solar plants. Optimal control techniques, such as model predictive control (MPC), can be used at this stage. The optimal operating points depend on the solar radiation, environmental conditions such as temperature, humidity, and wind, and plant operating condition such as temperatures of the main systems, reflectivity of the mirrors, and heat losses coefficients. Because the solar radiation is a fundamental variable, good prediction techniques for solar radiation are needed.

PV inverters should have ride-through capability [53], which denotes the ability to keep running after transient drops in the network frequency. Some PV inverters will keep working with up to 10% frequency drops.

5.2.2 Transmission systems

Key changes in future power transmission systems will include the transition from bulk dispatchable power plants to distributed, variable and nondispatchable generation, increased deployment of storage devices, and an increased level of demand-side management. These changes will not only result in modified grid topology and distribution pathways, but also the rate at which these flows vary and their predictability. The current rigid and centrally controlled transmission infrastructure is perhaps an obstacle rather than an enabler of the envisioned electric power grid. The transmission grid of the future needs to be rapidly adjustable to varying system conditions and must make optimal use of the existing and newly deployed transmission assets. In the following sections, we discuss key technologies and control paradigms that will enable the transition of current power systems status to what we envision should be the power system of the future.
5.2.2.1 Control architecture paradigms

Different control objectives in transmissions systems necessitate different architectures for information transfer and decision making. Two different architectures, each of which caters to a different goal, are presented in the following list:

1. **Hybrid architecture.** One of the first tasks for controlling the future grid effectively is to develop a control architecture that combines a centralized structure with decentralized elements. This hybrid architecture employs additional information on top of state estimation results following from SCADA energy management system (EMS) and information on system operating conditions. The wide-area measurement system (WAMS) technology can provide such additional visibility and controllability of the grid through high-resolution dynamic phasor measurement data.

![Diagram of a two-level hybrid architecture](image)

**Figure 5.2 – Two-level hybrid architecture that illustrates how a centralized controller could be combined with several decentralized controllers. The measurements conveyed by the central controller to the local ones may be predominantly SCADA-EMS based, while the local measurements communicated to the local controller might be based on PMUs. The remote measurements going from the local systems to the centralized controller could be a mix of SCADA-EMS, which have lower bandwidth, and PMU-based, high-bandwidth ones.**

A credible two-level control architecture composed of a centralized controller and many decentralized controllers using a WAMS is shown in Figure 5.2. Additional higher level controllers are also possible. The traditional decentralized control can accommodate smarter voltage regulation and damping control (power system stabilizer) at generators, primary and supplementary controls at FACTS equipment [51], or discrete control for switching capacitors/reactors banks, and generator and load trip. This decentralized level provides local
control action for which global information might provide additional actionable information. These controllers still have the fallback capability of using only local signals in the event of loss of communication links or a failure that makes the central control unavailable.

The effectiveness of a complex information-based control system such as the one shown in Figure 5.2 requires good dynamic models for tuning the control system parameters. As the system evolves, the controllers need to be updated so that the overall system performance will meet some desired specifications. After the control parameters are set, it is important that the overall performance of the control system be monitored. In particular, if some performance conditions are not met, the system operator should be able to determine which controllers are not working properly. It might be a simple matter of the controller not being implemented properly or the unwillingness of a particular system operator to share in the overall control effort. In the latter case, a penalty needs to be assessed.

2. **Distributed architecture.** A compelling argument for distributed architectures is their ability to introduce redundancy. If computers running the EMS software at the control center fail or are the target of a cyber attack, if the communication channels between the control center and the generators become unavailable (temporarily or permanently), or if the data becomes corrupted (e.g., due to a cyber attack), then it is obvious that the reliable operation of the system is in jeopardy. For example, if the frequency in the system goes outside prescribed performance requirements, the generating units underfrequency and overfrequency protections will take them offline, which could cause a significant loss of power generation. It is true that virtually all balancing authorities responsible for frequency control are likely to have two control centers with redundant computers and EMS software, which makes the event of losing both of them at the same time very unlikely. However, this redundant scheme is not resilient to: 1) coordinated cyber attacks on both EMS computers or 2) problems with the point-to-point communications between the control center and the generators.

A possible solution to make the automatic control system for frequency regulation stronger through dissimilarly redundant networked control. This notion is not intended to replace the existing centralized control system, which would be in charge during normal operation, but would serve as a backup. The idea behind dissimilarly redundant networked control is to distribute all the computations centrally performed at the control center throughout the network of units participating in frequency control, by having them exchange information with neighboring generators and making local computations based on this information. Specifically, each generating unit should be endowed with an ultrareliable computer; this reliability can be achieved through standard computer architecture solutions used in fault-tolerant systems for safety- and mission-critical applications (see, for example, Pradhan [77]). Each of these computers should be able to exchange information with the computers of neighboring generating units participating in frequency control; in particular, the information exchange between computers (from now on referred to as nodes) can be described by a (possibly time-varying) strongly connected directed graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V} = \{1, 2, \ldots, n\}$ is the vertex set (each vertex—or node—corresponds to a generating unit), and $\mathcal{E} = \mathcal{V} \times \mathcal{V}$ is the set of edges, where $(j, i) \in \mathcal{E}$ if node $j$ can receive information from node $i$ at time $k$. In the previous setting, the idea is for the generators to run a distributed algorithm that adheres to the constraints imposed by the communication graph so that they can compute their power output reference command for both secondary and tertiary frequency control. For secondary control, the problem boils down to a resource allocation problem, where a certain amount of power generation needs to be allocated among the set of
generators participating in secondary frequency control according to some predetermined participation factors. Solving this resource allocation problem in a distributed manner is doable; for example, it can be solved with linear-iterative algorithms as proposed in [37, 38] (the application in these works is different from the one discussed here). For tertiary frequency control, the problem is more complicated as it involves solving an optimization problem—referred to as economic dispatch—where the objective is for the generating units participating in tertiary frequency response to collectively provide a certain total amount of active power demand (subject to individual upper and lower capacity constraints), while minimizing the total cost of meeting this demand. When the communication graph is undirected, the problem can be solved in a distributed fashion using the ideas in [97] by using logarithmic barrier functions to augment the cost function so as to reflect the individual capacity constraints; more recent work exploits the specific structure of the optimization problem to derive a linear-iterative algorithm that also adheres to communication topologies described by directed graphs [36].

When the computations for secondary and frequency control can be implemented in a distributed fashion, the realization of a dissimilarly redundant networked system for frequency control is indeed feasible. As stated previously, the distributed implementation would be a backup for the centralized one; in fact, it is possible to use the same idea to implement several backups. In particular, we can assume that instead of one communication graph $G_x$, there are potentially $m$ communication graphs $G_{x1}, G_{x2}, \ldots, G_{xm}$, all of which share the same set of computing nodes that, as described previously, are ultrareliable. Every node implements $m$ copies of some distributed algorithm that allow it to compute its corresponding power output reference command, with each of these copies adhering to one of the $m$ communication graphs. In normal operation, whenever all of the communication links associated to $G_{x1}, G_{x2}, \ldots, G_{xm}$ are available and have not been corrupted, the solution provided by the $m$ copies should be the same; additionally, if the centralized control is working properly, the $m$ solutions should be the same as the one provided by the centralized controller. Whenever there is a problem with the centralized controller solution, each node should be able to independently detect this problem by comparing the reference command provided by the centralized controller with the $m$ solutions that the node is locally computing—effectively this constitutes an $m + 1$ voting system. Upon detection, the computing nodes in control of the individual generating units could ignore the commands provided by the centralized controller and revert control to the backup distributed implementation, which up to that point was being used for monitoring the performance of the centralized architecture. At this point, given that each of the $m$ distributed implementations relies on a different set of communication links, the system could potentially withstand $m – 1$ additional failures.

Although these ideas are appealing, there are several issues that are open and need to be addressed. For example, while we can ensure that the computing nodes are ultrareliable, and there are $m$ dissimilar distributed implementations, in the sense that the communication graphs associated to each of them do not share the same set of communication links, it is important to ensure that the communication links are reliable themselves. Additionally, the solution to the secondary and tertiary control command computation provided by the distributed implementation is the same as the one provided by the centralized one; it is necessary to ensure that the computational time involved in the distributed solution is similar to the one involved in the centralized solution.
5.2.2.2 Advanced protection schemes

A significant research challenge that is emerging on the Smart Grid scene is in the context of protection systems, which form the primary layer of defense against faults in power systems. Their role is to ensure that the high currents induced by fault conditions, such as lightning strikes or fallen conductors, do not cause damage or endanger lives. Protection takes many forms, including overcurrent, distance, and differential schemes. Protection devices must act extremely quickly to limit the energy delivered during a fault, and so tend to be reactive and myopic (i.e., upon detecting a fault, protection will operate in a predetermined manner without considering its impact on the wider system). Protection must ensure fast clearing of any fault at any location in the power system. Furthermore, in the event of a protection device failure, backup protection must operate to clear the fault.

Power systems currently employ a limited number of special protection schemes. Although the terminology is not rigorously defined, a special protection scheme is typically understood to be a set of relay switching actions, possibly together with a discontinuous change in some local controller structure, performed in response to a prescribed set of disturbance conditions. Such control schemes are set based on offline evaluations and triggered when the occurrence of a specific event is detected. These schemes must respond very quickly, and hence the limitations of existing technologies have typically dictated that they must operate based on easily measured, predetermined conditions. Advances in communications networking and hybrid controls will establish the foundations for more extensive and coordinated versions of such schemes. In particular, instead of relying on the event response approached provided by the aforementioned special protection systems, we need to move towards a closed-loop control based on system response. The event-response approach takes corrective actions after the onset of a disturbance, largely independent of the wider-area operating conditions in the overall system. On the other hand, a system-response control scheme applies corrective actions—based on real-time measurements and more sophisticated computation—that allow broader system conditions to inform the protective action (e.g., the relative stability of a given operating point). The higher bandwidth and improved communication speeds associated with synchronized phasor technology, along with much more powerful distributed computation, will enable these advances.

Power systems employ a second layer of defense to prevent unacceptable excursions in frequency and voltages. In the former case, underfrequency load shedding trips entire distribution feeders if the frequency falls below a preset threshold. Increasing amounts of load are shed until the frequency decline has been arrested. The rate at which the frequency decreases is dependent upon the inertia of the system, and the maximum frequency excursion is related to the amount of generation under governor control. Generators and loads that connect to the grid through power electronics do not contribute inertia to the system. Examples include most renewable generation, newer motor drives, and plug-in electric vehicle (PEV) chargers. Furthermore, renewable generation is generally not capable of governor action. Consequently, future power systems are likely to display frequency excursions that are faster and deeper than has historically been the case. Control-based solutions will be required to compensate for these changes in the system’s response.

Large voltage excursions tend to be associated with localized overloading of the supply network and often display behavior known as voltage collapse. It is anticipated that future power systems will be routinely operated closer to their limits, implying an increased likelihood of voltage collapse events. Preventative control strategies will require measurements from across the relevant subsection of the network, in order to formulate a corrective response. Actions can range from transformer tap blocking and capacitor switching to controlled reduction of critical loads.
Power systems must continue to operate reliably when any single item of plant trips out of service. This operating philosophy, known as the \( N - 1 \) criterion, provides the ultimate layer of defense against unplanned events. Unfortunately, \( N - 1 \) operation results in underusage of available plant. Advances in monitoring and control could, however, facilitate an alternative control-based approach that provided a commensurate level of reliability. The enhanced responsiveness needed to achieve such a fundamental change in operating philosophy would only be possible through active participation of loads and storage. For load to play such a role, though, control action would need to be nondisruptive (i.e., demand could be regulated without any impact on consumers). Such a scheme would respond to an unplanned outage by determining a trajectory of control actions that possibly adjust load and storage over a short-term horizon, while maneuvering generation to new longer term set points.

5.2.2.3 Advanced actuation systems for dealing with increased variability and uncertainty

The primary impacts of uncontrolled variable renewable generation resources on a power grid are system frequency regulation and reactive power support. Frequency regulation requires storage devices and fast-start gas turbines to coordinate with the renewable resources to maintain the system frequency close to the nominal system frequency. The extra challenge is the low inertias of renewable resources [68]. Transmission system control is also critical to ensure adequate reactive power support. If the sudden shortfall in renewable energy generation is largely compensated by additional output from nearby local gas turbines and storage, very little change in reactive power support is needed. On the other hand, if the shortfall of renewable energy in a particular region has to be compensated by remote generation, then the proper reactive power support would be needed to facilitate the additional power transfer, without causing voltage stability problems. Next, we discuss two technologies for transmission system control that have the potential to address the issues discussed previously.

1. FACTS. Control of FACTS can greatly influence operational reliability of the grid, specifically for transient stability and voltage and frequency control—problems that are particularly exacerbated by increased volatility and stochastic variability of wind, and dominance of asynchronous generators, which demand dynamic reactive power compensation for supporting the doubly fed induction generators (DFIG). In addition to responding to rapid transients, operation and control of FACTS in steady state conditions through real-time control of reactive power injection/absorption is becoming increasingly more prevalent for maintaining a safe voltage profile. However, nonlinearities, model uncertainties, and external disturbances demand a robust approach to control of such systems. At the same time, increased complexity, due to both increased number of active components of the grid and increased amount of data and sensor information, renders a centralized approach impractical. Thus, one must aim for developing a robust control framework for distributed control of FACTS and fast storage for improving operational reliability, risk mitigation, and preventing cascade failures. Although real-time control already plays a major role in operation of power systems, it is the addition of new sensing and actuation devices across the grid that presents the opportunities and the challenges. Although from a control systems perspective the fundamental problems of distributed control remain unsolved, this specific application area warrants both adaptation of the existing frameworks and further development of the theory.
2. **High-voltage direct current (HVDC) corridors.** Although HVDC transmission systems have been in use for many years [10], newer voltage-source converter (VSC) technology, generally referred to as VSC-HVDC [30, 94], is opening up a much wider array of applications. HVDC is particularly advantageous where long cables are required (e.g., underwater applications), with VSC-HVSC the preferred technology for connecting wind farms that are situated a substantial distance from the shore. Further applications will develop as the cost of power electronics decreases and capabilities increase, particularly where point-to-point energy delivery is desirable. Long-distance underground transmission becomes technically feasible with VSC-HVDC, and provides an option where right-of-ways are difficult to obtain.

The power flow over an HVDC link is fully controllable. By coordinating the control of sufficient HVDC links throughout the transmission network, power flow patterns could be regulated to minimize loop flows, thereby maximizing the network transfer capability. Tracking slowly varying quantities, such as loads and renewable generation, is straightforward and consistent with existing state estimation and AGC practices. Achieving a stabilizing response to large disturbances would be much more challenging, requiring subsecond cycle times for acquiring wide-area measurements, control algorithm computation, and control signal distribution. The power flow control offered by HVDC can also be used to enhance the damping of small-disturbance modal oscillations [29]. Such schemes would require fast and accurate measurements from across a wide area, as provided by phasor measurement technology. Careful analysis would be required to ensure HVDC links were robustly coordinated with other damping controllers, such as the power system stabilizers (PSS) of generators [17].

**5.2.2.4 The role of data in control and information systems**

The large dimension of linear and nonlinear power system models is one of the main control challenges in transmission. Conventional control design methods do not show satisfactory performance when applied to this large dimensional system. Even with a synchronized measurement system, many system variables cannot be measured, and the use of observers can compromise control performance because of the system’s high dimensionality. To overcome the challenges of future transmission control systems, the design methods must address output-feedback constraints and high-dimensional models. Because the power system operating point and parameters are always changing, the control methods must also exhibit robust properties.

Yet another natural consequence of the model dimensionality and widespread sensor deployment in the future grid will be the need for distributed computation and control. As we gradually move from today’s data-generating energy systems to tomorrow’s data-driven energy network, such distributed computational methods and data analytics will play substantial roles in grid operations. WAMS itself will require highly intricate, scalable, and decentralized data analysis techniques, especially with rapidly increasing penetration of intermittent renewable resources and plug-in hybrid vehicles. In the Eastern Interconnect (EI) of the U.S. grid, for example, even with just 100 phasor measurement units (PMU) streaming data by the Internet, the super-PDC (phasor data concentrator) located at the Tennessee Valley Authority processes nearly 2 billion data samples per day. This number is anticipated to grow as the number of PMUs increases to over 1000 in the next few years under the U.S. Department of Energy’s Smart Grid demonstration initiative [76]. As volumes of such data explode, the primary challenge for system operators will be to deploy fast and robust numerical...
algorithms for processing hierarchical levels of information derived from redundant data so that they can be employed for real-time monitoring and control applications.

One primary effort for control engineers will be to develop the framework of computational methods for tomorrow’s energy networks, which can vary over wide ranges of temporal and spatial scales, have both deterministic and stochastic dynamics, be influenced by socioeconomic factors, and adapt themselves with changing operating conditions [55]. The focus here will be on the modeling, monitoring, stability analysis, and control of large-scale power transmission systems with the objective of maximizing system reliability through distributed decision making. For transmission systems, applications will be defined over timescales ranging from tens of milliseconds to minutes, and spatial scales of tens to thousands of miles. To summarize, the computational challenges in such systems will primarily arise from the following drivers:

1. Analysis of local and interarea oscillation swings in interconnected power systems following major disturbances.
4. Adaptive automatic generation control (A-AGC) algorithms with moving boundaries of spatially distributed operating regions.
5. Optimization algorithms for wide-area power flow control using FACTS and HVDC.
6. Planning, siting, and designing of large wind farms for optimizing available transfer capabilities (ATC) of remote transmission lines.
7. Departure from centralized monitoring and control algorithms to distributed computing through cloud computing and virtualization.

We foresee the computational challenges for transmission systems to be the most challenging because of their underlying size, complexity, and dynamics. Sensitivity of these methods to time-varying operating conditions, load characteristics, and drastic changes in transmission topology also needs to be investigated. Impact of data or sensor loss and a resulting effort to make the computation adaptive and co-operative will be yet another critical factor.

5.2.3 Distribution systems

Along with the transmission system, the power distribution system will undergo dramatic changes in the future Smart Grid, each one of which is intricately interconnected with control challenges and opportunities. These challenges span distributed renewable integration, design of local communication networks, distributed state estimation, heterogeneous component control, design of distribution-level markets, protection, and self-healing. These aspects and the role of control therein are described in the next subsections.

5.2.3.1 Distributed generation

Locating large renewable power plants in the core of the grid is not sustainable for several reasons. First, it requires huge subsidies, especially with falling natural gas prices. Second, there is growing opposition to expanding the transmission system. Third, backup of large renewable generation requires large fossil fuel-based reserve generation. A better scheme is to locate small-scale distributed
energy resources (DER) (e.g., rooftop solar, community wind power) in the distribution system. The distribution system can be organized in intelligent clusters of DERs, which will be highly heterogeneous, and will have dynamics with diverse timescales and criticality of scheduling. Distributed generation (DG) resources with disparate temporal generation patterns (solar, wind, combined heat and power [CHP]) must be linked with collections of highly heterogeneous loads. At high DG penetration levels, the current practice of solving for optimal power flow is neither feasible nor economical. A technologically sound and practical approach is to enable them to self-organize into aggregated generation groups, each of which is represented by a virtual but functionally equivalent aggregated generator. Enabled by local communication networks, aggregated power dispatch can be achieved by implementing distributed cooperative controls at each of the DERs. Figure 5.3 illustrates the interaction and cumulative information flow among DG groups and the substation in a distribution system.

**Figure 5.3 – A distributed architecture of DG groups (OLTC=on-load tap changer; SVC: static voltage control). Judicious communication between the four DG groups and the substation and distributed control is needed in order to meet varying demand and accommodate renewable generation.**

Within each DER cluster, loads and renewables are coordinated so that the cluster is as balanced as possible, and provides voltage and VAR support, and other ancillary services. As a result, the burden on the transmission system is reduced, and reserve requirements are lowered. It might also be the case that the grid is now more resilient. The challenge is to design the cluster sensors (what should be measured) and communications and control architecture, and show that the claims listed previously are valid. The contractual structure of these clusters needs to be designed efficiently. Advanced control and coordinating approaches and solutions are required for stable distribution grid operation with quality power supply to the consumers.
**5.2.3.2 Design and implementation of local communication networks for distribution networks**

To maximize the use of DG resources while scheduling and meeting dynamic demand and maintaining grid stability, sensing, optimization, and control algorithms must be designed in concert with an underlying real-time communication and networking infrastructure. Indeed, a core tenet of the Smart Grid is that all aspects of the power distribution network will be closely coupled to a communication network that enables efficient management of power flows across temporal and spatial scales. A range of architectural and implementation options for the communication network infrastructure are possible, along with a host of physical-layer alternatives; these include power line communication (PLC), the wired Internet, or one of many wireless network protocol options. Here we outline how the distributed sensing, optimization, and control (SOC) needs of the Smart Grid will drive and interact with design requirements for the communication network.

Tomorrow’s communication networks for the Smart Grid will almost certainly be hierarchical, with at least three subnetworks spanning the distribution grid, clusters of microgrids, and individual users or homes, each with different constraints, requirements, sensing modalities, and computational capabilities. This hierarchy is associated not only with diverse sensing and control needs of the subsystems, but with inherent design constraints associated with spatial coverage and power flow dynamics. The core requirement is that the communication network must meet the real-time demands of Smart Grid SOC across the power/communication network hierarchy. These demands will drive requirements for communication network latency, bandwidth, and reliability that flow from analysis of distributed SOC algorithms incorporating models for delay and information loss.

As a consequence, there is a need to develop new theories and designs for distributed SOC that are robust to communication network errors and failures as well as delays and losses. At the same time, algorithm synthesis must be informed by communication network properties, including performance margins and redundant functions.

Based on these observations we can forecast two trends as we look ahead to 2050. First, an efficient and robust Smart Grid will require co-design of distributed SOC algorithms and communication networks, in turn motivating research on new theory and tools for joint analysis and cosimulation across the power and information-flow domains. Second, there will be an increasing need for sophisticated experimental test beds that merge simulated and physical components and subsystems, enabling real-time and scalable testing and validation of SOC algorithms. In the context of these trends, the following research questions should be addressed:

- What are the bounds on reliability, throughput, and latency required to ensure stability and optimal flows?
- What sensing modalities and sampling rates are required to assure stability and optimal control?
- The distributed nature of these systems implies that sensing, optimization, and control functions may themselves be distributed. Where should the intelligence be located to accomplish these functions, and how should the communication network connect them?

**5.2.3.3 Distributed state estimation**

Due to the expansive nature of distribution networks, it is not economically feasible to make all intelligent electronic devices (IED) and their communication secure, or to store all data at a secure central location. Nonetheless, the properties of physical distribution networks can be exploited to
develop distributed state estimation methodologies. Through the use of neighborhood area networks and by linking user area networks to the Internet, local data can be collected, stored, and processed using cloud computing resources. Such distributed and cloud-based schemes enable DGs and other DERs of limited storage and computation capacity to detect physical faults as well as data inconsistencies in distribution systems. A specific application is how to detect the islanding condition and to ensure safe islanding operation in a distribution network containing many DERs.

5.2.3.4 Closed-loop control of heterogeneous components

In addition to distributed generation, distribution systems contain heterogeneous devices including on-load tap changers (OLTC), switched capacitor (CAP), static VAR compensators (SVC), distribution static synchronous compensators (DSTATCOM), and storage elements. These devices have different response speeds in voltage regulation: minutes and longer for OLTCs, around one minute for CAPs, 10 ms to 100 ms for DGs, and 10 ms or less for FACTS devices. Their inputs/outputs are also different: discrete for OLTCs and continuous for the others. Accordingly, their actions need to be coordinated and controlled to account for these different timescales, leading to enhanced operation with minimal participation from the operators during normal operation. For instance, transformers with OLTC should be controlled mainly for the steady-state voltage regulation and with consideration of varying capacity of DGs, and DGs and FACTS devices should be controlled to avoid voltage flicks and compensate for voltage sags. Each of these applications have dedicated control objectives and scopes, which have to be optimized for a look-ahead time horizon to avoid short-sighted decisions because of limited resources and control constraints along with the time. These applications have to be well-coordinated over the optimization horizon for the overall optimal solution without resulting in any control conflicts, overshooting, or undershooting among all the applications.

5.2.3.5 Distribution-level markets and reactive power control

Substantial benefits will accrue from the creation of distribution-level power markets. In the first place, incorporation of marginal distribution line losses and the decay of transformer assets in electricity rates will provide the needed incentives for flexible loads to adapt their consumption, which will make distribution infrastructures better able to cope with the desired growth of flexible loads and distributed resources such as EVs and roof top PVs. Sources of reactive power will expand, bringing substantial efficiencies and cost savings. Traditionally, reactive power compensation has been supplied by just a few generators, usually gas-fired, located close to urban load centers, and is now increasingly provided by trailer-size solid-state dynamic VAR compensators, located at or close to substations. Soon, this picture will change radically with the introduction of many moderately sized (10 to 50 kVAR) inverter-type power electronic devices embedded in PV installations and electric vehicles. With minor modifications, a 30 kW solar inverter or the 50 kW inverter/rectifier found in every Toyota Prius can be put to dual use: when the sun does not shine or a hybrid vehicle is parked, the inverters can compete to supply reactive power in response to retail market locational price signals. With minor modifications, they can act as small distributed dynamic VAR compensators with zero cost that produce or consume reactive power to reduce the flow of reactive power injected into the distribution network at nearby locations by inductive/capacitive loads or the distribution network itself. Heretofore, because there were so few providers of reactive power, creation of competitive markets was not warranted. The establishment of markets will give larger sets of providers strong incentives to eliminate undesirable voltage-current phase shifts. Such elimination will significantly reduce distribution line losses, which account for well over 5% of total electricity production and assist with voltage control.
5.2.3.6 Bidirectional flow

Some of the largest impacts that distribution systems will have to contend with in the future will come from the direction and variability of power flows resulting from distributed photovoltaic generators. If future distribution systems have massive amounts of photovoltaic generation capacity behind customer meters, the spatio-temporal variation in power flows on distribution circuits will become much more complicated. Changes in production due to cloud transients will be correlated across systems; the strength of this correlation will depend on the weather regime, time of day, and module orientation. Understanding and forecasting the dynamics of these power flows will be central to anticipating the impacts that photovoltaic variability will have on voltage regulation and protection systems.

5.2.3.7 Protection, self-healing, and islanding

The implementation of dynamic distribution network reconfiguration in real time for enhanced grid operation efficiency and reliability, along with the high penetration of distributed generation, will introduce great challenges to relay protection in distribution grids and microgrids. The conventional protection mechanisms with static configurations based on offline analysis will not be possible to properly provide the protection needed. Dynamic and adaptive relay protection mechanisms are required for effective distribution grid protection.

With more and more distributed generation connected to the distribution grids, issues on operation stability, frequency, and voltage controls will become an important part of the reliable distribution grid operation, especially for microgrids and the part of the distribution grid that is in an islanded condition. Advanced analysis and control mechanisms have to be developed to cope with the challenges.

Distributed IEDs with embedded analysis and control logic can perform self-healing and intelligent controls through meshed communication among the local IEDs, such as Volt/VAR and fault detection isolation and restoration (FDIR) controls. The localized control logic, configuration, and set point controls could be downloaded from the centralized distribution operation management system.

5.2.4 Summary of research challenges

The following is a list of research challenges pertaining to current topics in power systems including generation, transmission, and distribution:

1. Wind turbine active power control (APC) systems, which allow wind turbines and wind farms to participate in grid frequency regulation and provide frequency response to sudden changes in grid frequency.

2. Active power control (APC) over a wind farm, considering the structural loading induced by the actions of upstream turbines.

3. Enhancements to wind forecasting and power regulation markets to enable wind energy, when curtailed, to participate in the regulation of grid frequency.

4. Decreasing the degree of uncertainty in predicting solar radiation based on the analysis of satellite images, ground-based sensors, cameras, and solar plant output from other locations.

5. Optimal plant wide control of thermal solar power plant and enable adaptation to changing plant and environmental conditions.
6. Algorithms for tracking the sun in heliostat field to obtain a uniform flux distribution in solar towers.

7. Development of a resilient and efficient hybrid control architecture for transient stability that combines a centralized structure with decentralized elements so as to optimize global outcomes using local information and coordinated actions.

8. Development of computationally efficient distributed architectures for transient stability with suitable redundancies that ensure protection to failures (example: communication lapses and cyber attacks).

9. Enhanced protection against faults by a synergistic participation of loads and storage and a predictive approach over a short-term horizon, while maneuvering generation to new longer-term set points.

10. Distributed control using FACTS and fast storage for improving operational reliability, risk mitigation, and preventing cascade failures.

11. Coordinated control of HVDC links so as to minimize loop flows and maximize network transfer capability.

12. Stabilizing response to large disturbances in subsecond timescale in transmission systems.

13. Design of DG clusters in terms of the type of sensors and communications and control architectures that can enable efficient and reliable power flow. Appropriate contractual structures need to be designed that facilitate these goals.

14. Theories and designs for distributed SOC that are robust to communication network errors and failures as well as delays and losses. Algorithm synthesis must be carried out from a control perspective that accommodates communication network properties, including performance margins and redundant functions.

15. Distributed state estimation methodologies that efficiently use neighborhood area networks and the cloud to collect, store, and process local data. The use of estimation to detect physical faults as well as data inconsistencies such as islanding and to ensure safe islanding in the presence of several DERs.

16. Coordination and control of heterogeneous components such as OLTC, CAP, and SVC that possess different timescales, so as to lead to enhanced operation with minimal participation from the operators during normal operation. Simultaneous optimization of multiple control objectives and scopes, over a suitable time horizon, without resulting in any control conflicts.

17. Efficient control of reactive power and voltage control using distribution-level power markets by providing incentives for flexible loads and distributed resources.

18. Transient stability, frequency, and voltage control in the presence of islanding in microgrids.

19. Fault detection and restoration using distributed IEDs and meshed communication.

5.3 **Loci of control: Emerging centers of activity**

The central challenge introduced by renewable energy sources pertains to the intermittency and uncertainty of their availability. A large penetration of these sources has ushered in emerging centers of activity that encompass new market mechanisms, automated demand response, optimization of
storage and electric transportation to meet grid needs, and the design of microgrids, virtual power plants, and aggregators. Control is a central actor in all of these problems. Its role is explored in the sections that follow.

### 5.3.1 Electricity market mechanisms

An electricity market mechanism is an equilibrium process by which electric energy resources, such as demand, supply, transport, ancillary services (e.g., reserves), and storage are managed using various pricing mechanisms. The wholesale electricity market was established in the U.S. in the 1990s following deregulation in order to ensure that power generation is efficiently scheduled to meet the demand [74]. Various mechanisms have been implemented for electricity markets such as locational marginal (nodal) pricing, zonal pricing, reserve and ancillary services pricing, bid-based security constraints, capacity markets, and time-of-use pricing.

Greater penetration of renewable energy, demand response, electric vehicles, and distributed storage will dramatically increase uncertainty while introducing large numbers of independent actors in the electric power system. The inherent intermittency and uncertainty in the renewables, together with hard constraints of energy balance, transmission congestion, and fluctuating demand, point to the need for fundamental changes. Achieving Smart Grid objectives will require new methods, new tools, new architectures, and new solutions for market analysis and synthesis.

Wholesale markets are typically organized as multiple-settlement uniform price auctions based on locational marginal price (LMP) that are run daily by independent system operators (ISO) [26]. They consist of a day-ahead market (DAM) and a real-time market (RTM), each producing its own financial settlements in which ISOs are responsible for both day-ahead auctions that are run daily for each hour of the following day, as well as real-time auctions that are run every 5 minutes during the day. In some cases, there are additional intra-day market based adjustments. Generators participate in these markets by submitting offer curves consisting of generation levels and energy prices as well as start-up costs, no-load costs, minimum up and down times, and other technical constraints and costs. The most common and powerful tool for determining optimal solutions to financial settlements in both the DAMs and RTMs is optimal power flow, whose use is ubiquitous in electricity markets since deregulation.

There are many differences in specific implementations of DAM and RTM among ISOs and regional transmission organizations (RTO). Generally speaking, in the DAM, supply offers, demand bids, and renewable forecasts are combined for joint optimization of energy and ancillary services (AS) for the next day. The DAM is run without any specific accounting for the RTM decisions that will be made subsequently, except for the AS capacity decisions in DAM. Although RTM does depend on the decisions made in DAM, demand bids are not accepted in RTM. Moreover, the uncertainties in load and renewables are treated with decoupled point forecasts rather than full joint distributions [20, 26, 57, 69, 74, 78, 84, 95].

From a control theory viewpoint, economic optimization of the power/energy system subject to security/reliability constraints in the presence of uncertainties in the load, renewable generation, and the power network is a multi-stage stochastic dynamic programming problem. It is evident that the current practices in DAM and RTM described previously represent suboptimal solutions to the underlying stochastic dynamic programming problem. Furthermore, attempting to guarantee security (e.g., in the form of loss of load probability), while ignoring the evolution of conditional probabilities of load and renewable generation and guaranteeing security, leads to very conservative decisions. The key challenge, therefore, is to formulate the dispatch process in the framework of a sequential,
stochastic control problem with probabilistic forecasts of renewables and loads, and with risk incorporated as a cost rather than a rule of thumb such as 5% of peak load [78, 95]. Although such a change in market structure represents a daunting administrative challenge, the benefits with regards to cost savings could justify such changes. Moreover, the introduction of distribution-level marginal prices promises to have transformational impacts on power systems in terms of electricity costs, infrastructure resilience, and the wide integration of renewable generation and sustainable new loads such as electric vehicles. But to realize the full range of potential benefits, it will be essential to adopt the right pricing structure and market reforms.

Given the significant impact that increased uncertainties stemming from renewables can have on market transactions, accurate forecast modeling is a crucial ingredient in determining resource dispatch. Given the trend in more accurate forecast models for entities, such as the weather and demand, over decreasing horizons, a multiple timescale market model that incorporates the varying forecast models and their modeling errors needs to be developed. Intermittency will also lead to a growing need for fast and flexible reserves that can be used to maintain energy balance in real time by absorbing positive and negative fluctuations in renewable generation. Currently, these type of fast reserves are provided through regulation service reserves (RSR), which are procured in the hour-ahead or day-ahead markets but are actually used to track ISO regulation signals issued every five seconds. If the same practice were to be maintained, a 30% increase in renewable generation will imply a three-fold to four-fold increase in RSRs. Because RSRs clear today at prices comparable to energy clearing prices, to increase their supply under existing conditions will pose a significant barrier to renewable generation expansion. These higher RSR costs might be avoidable if the reserves can be obtained from flexible building loads, and EV battery charging. This synergy can be achieved by efficient market price signals that provide flexible loads with the requisite incentives to consume energy when it is abundant and supply RSRs when they are needed. Concurrent adoption of EVs and renewable generation to fuel them will yield the dual benefit of reducing both CO₂ emissions as well as reliance on imported oil.

Based on the foregoing arguments, some key system and control-theoretic challenges that need to be addressed for next generation electricity market mechanisms are as follows:

1. Representation of the uncertainty in wind energy in market bidding.
2. Optimal bidding of independent wind producers into the day-ahead market and building hourly offer curves.
3. Hedging mechanisms against liquidity risk, market risks due to volatility, and operational risk due to uncertainty in wind power, unreliable equipment, etc.
4. Optimal penalty costs for deviations in wind production.
5. Modeling the impact of intermittency and uncertainty in renewables on ancillary services.
6. Integration of suitable demand-response models into both DAMs and RTMs.
7. Incorporation of storage and plug-in hybrid electric vehicle costs into the market architecture.
8. Design of intraday markets and market mechanisms that incorporate some or all of the previous items over a range of timescales.
5.3.2 Demand-response

Unlike any other major industry, the power grid developed under the fundamental assumption that demand always remains inelastic. Traditional customers consumed as much power as they wanted, whenever they wanted it, and accepted a feedback mechanism (monthly reporting and billing for their consumption) with a one-month time delay. These customers’ demand, with all its stochastic variation, was matched by adjusting generation and a variety of market and engineering mechanisms.

Demand response denotes the concept of adjustable demand in response to grid conditions and incentives and has a history dating back at least to the late Fred Schweppe’s pioneering work on homeostatic grid control in the 1970s. In the energy environment of the twenty-first century, demand response is an emergent actor in Smart Grid. It appears to have a significant potential in managing uncertain and variable renewable generation by allowing both consumption and generation to be adjusted. This effort, in turn, puts control on center stage, as it facilitates a blueprint for efficient modulation of consumption so as to efficiently integrate renewable generation and deliver reliable and affordable power (see Figure 4.4). In the subsections that follow, we articulate three different centers of activity in demand response where control plays a dominant role: 1) markets and pricing, 2) dynamic modeling, and 3) demand-side management.

5.3.2.1 Demand-response, markets, and prices

![Figure 5.4 – Simplified effect of demand response on electricity market prices [2](image)](image)

Today’s power markets already make utilities aware of their startup, shutdown, operation, and maintenance costs in the context of the physical limitations of their generation, transmission, and distribution facilities. As the concept of real-time price becomes better understood, the same awareness and decision making will begin to be extended into instrumentation and control for demand-side entities, thereby introducing demand response–compatible consumers as market players as well as a more balanced and dynamic relationship between power supply and demand. Some examples of these schemes are supply-driven, incentive-based programs like interruptible rates and emergency demand response. These examples have been observed to lead to price elasticity [48]. More recently, marginally successful price-based programs have been developed to include tiered time-of-use rates and real-time pricing markets [2].

Demand-response brings in the need for a dynamic framework for addressing the financial settlements. The temporal components are necessary because of intermittency and uncertainty in renewable generation and the feedback structure inherent in demand response. Real-time price can be
viewed a state of this dynamic framework, because it is determined through financial transactions of various market entities, and as a feedback control variable, because it can affect consumption. The interrelationships between demand, real-time pricing strategies, and financial transactions, grouped under the rubric of transactive control, necessitate a dynamic framework of study to integrate renewables and demand response–compatible devices, social efficiency, and stability. Several challenges need to be overcome to develop such a transactive control method:

- Dynamic market mechanisms will become increasingly important as one moves from a day-ahead to a real-time market and the underlying forecast models of renewables and consumer and load control behavior become more accurate. The notion of disequilibrium process, often used in econometrics, might be relevant in this context.
- Any available information about market participants such as bids and offers need to be judiciously used.
- Consumer and load control behavior with their distributed decision making needs to be modeled and integrated.
- A temporal evolution of prices might be needed, not only at the wholesale level, but also at the retail level, in order to reflect the inherent dynamics present in demand-side entities. Stability and performance must be maintained both for prices and for power flows in the grid.
- Real-time and closed-loop demand response will result in a coupling of energy resources and markets at timescales that have the potential to cause stability problems. Achieving system performance and agility to external factors simultaneously with some robustness is a formidable task.
- A systematic stability framework that analyzes the interplay between pricing strategies, adjustable demand, and generation while guaranteeing stable behavior is highly warranted.

5.3.2.2 **Modeling of devices, forecast, and consumer behavior**

**Device modeling**

Heating, ventilation and air conditioning (HVAC) equipment, industrial motors and pumps, lighting systems, white goods appliances, computer and information technology equipment, entertainment and media systems, and building elevators are just some of the overwhelming number of diverse consumption sources in facilities. To realize a fully demand response–compatible consumption, these devices and systems need to be automatically managed within broad authority (and with override authority) of the facility owner, operator, or tenant. For this goal to be accomplished effectively, electricity consumption and performance must be subjected to a common mathematical modeling formulation with specific attention to various dynamical aspects—startup and shutdown, delays and time constants, dependencies on environmental factors and among related systems, efficiencies and usage guidelines at different operating points, ability to be curtailed and scheduled, etc.

Several challenges arise in determining this common modeling framework, due to the fact that several constraints arise from the underlying physics as well as performance specifications and constraints. For example, how can thermal storage in buildings be optimally scheduled and controlled given uncertain predictions of weather and load on a summer afternoon under dynamic pricing? What extent of energy should be used for precooling water, chilled water, or ice storage so that costs are
minimized and occupant comfort and building operations adequately maintained? What level of demand relief could be provided to the utility?

**Forecast modeling for loads and weather**

Two main sources of uncertainty that need to be contended with while realizing the demand-response future vision are weather and consumption. For load modeling, data-centric techniques are especially promising and offer numerous opportunities for research. These include forecasting with pooled data of similar types (day, hour) across a range (years, months) to estimate regression coefficients, and models from other, similarity-weighted facilities, automated classification of facilities and their consumption patterns, online updates as more data is collected, tractable uncertainty representations, and improved classification with more facility information.

Weather forecasting is required for predictions of load as well as wind and solar power. The underlying physics of wind and insolation are at least broadly understood, but the spatio-temporal complexity of the fundamental models is daunting. Computational improvement in these methods is an area the control community can contribute to.

**Behavioral modeling of consumers and organizations**

The increasing role of consumers makes the modeling of human behavior, especially in terms of decision making in energy-related activities, a crucial research topic. In particular, modeling of humans as consumers, facility operators, and occupants need to be the focus of this effort. This model should also capture the effect of variations in populations, both in physiological responses (such as sensitivity to temperature and humidity) and in cognitive processes.

Key cognitive human factors that will affect the uptake of demand response include latency, learning, and fatigue. These factors must be modeled if closed-loop control and optimization for demand-side management is to be effective. For example, a frequent concern of utilities with demand-side-management programs is customer fatigue—efficiency and conservation measures taken by residential consumers in the early phase of a new program for dynamic pricing might not be sustained over time. One way forward in the mitigation of demand-side fatigue is the quantitative modeling of electricity customer preferences. How, where, and when homeowners and renters use electricity depends upon individualized lifestyles. Consumer preference or utility functions provide a quantitative framework in which consumer preference can be harmonized with cost incentives. Initial work on temperature, humidity, and lighting preferences has been completed [41, 92], but much work remains to expand the scope to time-sensitive factors (e.g., television/Internet use, water heater patterns) as well as their integration into automatic control systems.

Organizational units such as commercial and industrial facilities are a complicating factor when it comes to behavioral modeling. Economics, environmental concern, production, and comfort requirements vary by sector and company. Furthermore, decision making and control in organizations has its own complexities.

It could be argued that human and organizational models, especially related to decision making and feedback, have not received sufficient attention in the controls community. However control theoretic ideas and tools are broadly applicable to problems in these areas, and the addition of these types of models is crucial if the full potential of demand-response programs is to be realized.
5.3.2.3 **Demand-response and demand-side management**

As better understanding emerges about demand response and the design of flexible demand-side entities, demand-side management, with appropriate assets and instrumentation, can serve as ancillary services, which enable fast adjustments and realize power balance. A term traditionally used for services provided by generators, *ancillary services* using demand-response applications are being demonstrated for some fast-response services such as frequency regulation [58]. Together with advancements in control technology, increasing implementation of distributed generation and storage technologies in particular might allow the full spectrum of ancillary services to be served by customer facilities in an automated fashion. New challenges that arise in this context include the consideration of real as well as reactive power, multiple-timescale coordination, and fundamental feedback/feedforward and regulatory/ supervisory control strategies.

Direct load control should be considered in the demand-response toolset in this context. The assurance that direct load control can provide for modifying facility consumption might be necessary in some contexts—an obvious example is avoiding imminent blackouts. The coordination of direct load control with price-based demand-response signals is another important topic for research. Other elements such as peak shaving, valley filling, load shifting, strategic conservation, and load growth should all be integrated into demand response, leading to a single picture of flexible supply and demand.

5.3.2.4 **Cost versus utility of power demand**

Unlike electricity generation, which is primarily cost-driven, electricity demand is sensitive to both the cost and the utility of power. Hence, an adequate description of demand response must center on the trade-offs between the costs and utilities that the user experiences. The resolution of the trade-off can vary substantially among residential, commercial, and industrial users and even within these sectors. The complexity of the problem arises in part because of the difficulties of quantifying utility in many cases, and in part because of the uncertainties involved—as a result of incomplete knowledge as well as future projections. A risk management framework, informed by dynamics and uncertainty, is required.

5.3.3 **Storage and electric transportation**

Cost-effective, high-efficiency storage and intelligent transportation mechanisms have incredible potential for aiding in the transition to a more sustainable power system. For decades, the requirement in electric power management was that generation needs to match load at all times. A hierarchical control structure consisting of primary, secondary, and tertiary control was developed to dispatch generation at various timescales, ensuring that load is supplied and frequency is kept close to its nominal value. Introducing an increased amount of storage capacity into the system provides a means to decouple generation and load, which is highly desirable in a future with a significant amount of nondispatchable generation from wind and solar generation. Early simulations confirmed its utility for peak shaving [47, 99]. Storage can also be used for frequency regulation [67, 75], ancillary services, and increasing both the efficiency [11] and economic value [35, 83] of renewable generation plants. However, the state of the art in large-scale storage technology cannot cost-effectively meet these goals. In addition, current market mechanisms and associated regulatory policies limit economic incentives for further developing these technologies [40]. Over the next decade, there will need to be a paradigm shift in what constitutes storage and the ways in which it is used. Small distributed storage will emerge as an important contributor to ancillary services both for
load following and fault recovery. Many electric vehicles are already equipped with devices that can be used to control their charging schedule. Flexible loads and electric vehicles will play larger roles in this new storage paradigm as flexible storage capacity. As discussed in the previous sections, new advances in distributed control of demand-side resources that need to take into account consumer behavior are necessary steps in developing such a system. Any communication and data requirements, as well as a plethora of uncertainties, will also need to be accommodated in this paradigm. The depth and breadth of controls and systems theory makes our community well-poised to play a role in meeting the challenges of a new storage paradigm.

Challenges with regards to control arise from the new opportunities for time shifting of load and generation provided by storage (i.e., when should excess power be generated to feed into the storage and when should stored energy be used to help meet demand?). Additional challenges are introduced because storage has limits on both available power (rate of energy charge/discharge) and energy (MWh) (i.e., the current availability of storage is tied to past usage). The size (scale) of a storage resource determines the applications to which a particular technology is best suited (e.g., small-scale storage devices are most suitable for balancing the fast, or small-scale, load variations, which is currently being done through primary frequency control). The role of secondary control is to free primary control reserves, to bring back frequency to its nominal value, and re-establish the power flows on the tie-lines between control areas. Again, the limited amount of available energy from storage might hinder a straightforward integration into the existing automatic generation control scheme.

Another aspect to consider is that the potential for renewable generation varies with geographic location. One area might have significant wind resources serving a significant amount of load in another area with fewer resources but with storage capabilities. For overall optimal performance, the storage in one area should be coordinated with the varying generation in the other area resulting in varying tie-line flows. The contribution from control engineers in this case is to provide the means to optimally coordinate the control areas without the requirement for extensive information exchange between the areas using wireless communications. Networking between these devices and grid control units will allow more effective decision making. However, the ad hoc availability of resources (i.e., electric vehicles connecting and disconnecting or customer behavior) will require real-time coordination, with capabilities beyond that of the state of the art of distributed control theory. The high connectivity between the system and human behavior also means that adaptive methods that can compensate for abrupt changes in behavior are critical. For example, if an electric vehicle that generally provides peak shaving while its owner is at work is suddenly needed for midday errands, the system must respond without adverse consequences for either the power grid or the vehicle performance. Developing suitable control architectures to handle the communication, control, agent, and device interactions poses new challenges for the control community. These new architectures will also require more transparency across layers (i.e., those between load, utility, and ISO) than the current infrastructure allows. The controls community can play a role in finding robust and secure means of transmitting information across these layers in ways that permit feasible and stable control actions. In the market and policy arena, the separation between storage and other resources is somewhat artificial. Thus, the questions of how consumers (who own storage resources) will be integrated with market models and the mechanisms that will be used to reward behaviors are crucial aspects. Systems and control scientists need to find ways to model these agents, analyze behavioral responses to economic incentives [40, 50], and develop a holistic view of designing markets that addresses all the previous issues [15, 35, 47, 83].
Transportation technologies such as PEVs are expected to advance significantly in the years to come. Although these vehicles are additional loads in the system, they can also provide storage capabilities to the system by employing vehicle-to-grid concepts. Currently, rail transportation energy needs are supplied entirely from a rich portfolio of electrical sources by the grid. Using widely distributed storage in new battery technology, flywheels, and fuel cells, nearly 100% of wind and solar energy renewables will need to be captured and stored at the wayside or onboard the transportation assets until required. In new collaborative infrastructure among utilities, private freight railroads, and newly revitalized public institutions, world-wide energy pricing and operations planning will need to be coordinated to reduce peak demands and the attendant charges. The complex dynamic interactions among transportation scheduling for passenger and freight and the impact on electrical load will need to be captured using new theories for hybrid and discrete systems applied to the resulting transportation-energy collaborative systems.

Decisions about whether to use and where to locate energy storage sites (e.g., at the wayside, onboard some or all of the rail transportation vehicles) need to be made with consideration of energy supply costs traded against needs to meet transportation constraints for goods and people delivery. Dynamic feedback strategies using advanced MPC methods might have to be employed with a suitable communication infrastructure to optimally accommodate the stochastic variation expected with a high penetration of renewable energy sources. For example, a fully charged transportation vehicle that remains parked at a station must be empowered to supply energy into the grid to ride through a peak load situation and avoid excessive demand charges. Similarly, fleets of personal EVs parked at commuter stations should flexibly absorb or supply part of the load during the day.

5.3.4 Microgrids

Facilities that have multiple types of loads, onsite generation, onsite storage, and the ability to function off the grid, in whole or in part, are candidates for microgrids, another Smart Grid technology that is generating considerable interest today [60, 61, 81]. Microgrids are small power systems of several megawatts or less in scale with three primary characteristics: 1) distributed generators with optional storage capacity from devices such as batteries, supercapacitors, or flywheels, 2) autonomous load centers, and 3) the capability to operate interconnected with or islanded from a larger grid [24]. Intelligent microgrids require systems that can measure, predict, and autonomously control their energy flow. As a consequence, well-designed energy management systems with components such as load controls, smart metering, generator monitoring, and power conversion technologies serve as their core. These components should be collectively designed so that they meet strict power quality and operational requirements.

Microgrids can serve as ideal platforms for realizing combined goals of a Smart Grid, including reliability, integration of renewables, diversification of energy sources, and flexible demand response. Because of their scale, they facilitate systematic, yet innovative, approaches to solve local as well as global energy needs. They can also provide facilities and communities a certain level of independence from grid disruptions while providing grid operators and utilities an additional resource for improving their operations.

In some respects, microgrids can be significantly more complex—for example, they might include DC elements and inverters for conversion, they can exert greater control over a wider variety of loads, and the connection with the grid can be flexible. On the last point, microgrids can enable uninterrupted operation where grid supply might be unreliable. In this case, the islanding capability of a microgrid comes into play. Intelligent microgrids have to optimally manage interconnected loads.
and distributed energy resources (including renewables) both in grid-connected and islanded modes. Moreover, in case of an emergency, such as the failure of a critical node or loss of utility power, an intelligent microgrid has to make critical decisions urgently—islanding might need to be in effect within subsecond timescales to avoid damaging equipment. There have been promising advances in technology in laboratory microgrids, but in general they are still not applicable to real systems, mainly because of flexibility and stability issues [88].

The loci of control research in this topic are expanded further in the subsections that follow.

### 5.3.4.1 Coordinated and distributed microgrids

Appropriate interface electronics (e.g., inverters) and advanced algorithms are required to perform coordinated control of a large number of distributed generators and storage devices to maintain instantaneous active and reactive power balances, power flow, and network voltage profiles. Transitions from one operational mode to another can cause imbalances between generation and loads, thus causing frequency and voltage control problems. A further technological challenge for microgrids is related to synchronization after changes in operating mode and in load/generation balance. Moreover, large-scale penetration of renewable energy sources (RES) requires the use of energy storage systems with appropriate parameters (e.g., size, power/energy ratio, charge/discharge rates). In other words, although high penetration of RES is desirable for many reasons, renewables are generally intermittent and their fluctuating patterns can create instability within a microgrid and lead to failures [25, 71, 80].

One can envision a power distribution system with heterogeneous distributed energy resources, PEVs, intelligent appliances, and other controllable or uncontrollable customer load demands as a virtual microgrid (VMG) [62]. The VMG is a cyberspace concept that allows changeable segments of distribution networks to be managed as microgrids—a VMG can have a dynamic topology and can be configured electronically to facilitate certain operational objectives. Alternately, when a section of a feeder is severed from the main grid, loads and generation on that disconnected portion could operate as an autonomous VMG. Local controls would be required to establish and maintain generation-load balance, and regulate voltages to an acceptable profile. The composition of such a microgrid would be highly variable, ruling out centralized control structures. The resulting distributed controls would be reliant upon a communications network that links microgrid participants. Similarly, branches of a distribution feeder could become capacity constrained, with overload prevention requiring coordinated operation of downstream loads, generation, and storage. Such constraint-induced microgrids would require distributed control algorithms that are consistent with those of autonomous microgrids.

Finally, a large number of information inputs need to be collected and processed to best manage microgrid operations. Measurement errors and inaccuracies are always inevitable, and distributed state estimation calculations need to be integrated into the online management system of a microgrid to truly realize its technical benefits [88]. Challenges also arise from the scale of the problem and its nonlinear, mixed-integer, and stochastic aspects [86].

An example of a microgrid architecture is shown in Figure 5.5. In this figure, a 12-kV microgrid is shown in both stand-alone and grid-connected mode. In the stand-alone mode, the system can supply an isolated load by means of distributed renewable energy resources (DRER) such as wind and solar power, and distributed energy storage devices (DESD) such as batteries and plug-in-hybrid vehicles. In the grid-connected mode, the system can either draw power from the grid in peak load conditions, or supply power to the grid during base load operation. In either modes of operation, the system is
based on a distributed intelligence infrastructure whereby smart devices such as solid-state transformers (SST) and fault isolation devices (FID) can communicate with each other over a secure communication network for the purpose of cooperative energy routing, energy automation, disturbance isolation, and demand response. The grid-connected system also takes in significant amount of information from the electricity markets, as well as data on customer participation and management from smart phones and other personal electronic devices. One important aspect of this data is when customers want to schedule their PHEV charging needs across various charging stations in a certain geographic area that falls under the operating zone of the distribution system. Another important feature of this smart microgrid is its plug-and-play capability, meaning that the system can be plugged in and out of the legacy grid, as needed, without any significant problems with synchronization. A DC microgrid will be the ideal option in that situation. The system will then become equivalent to a laptop computer that can be plugged in to the wall outlet as needed and taken out when the need is over.

**Figure 5.5** – A smart distribution system that can operate in both stand-alone and grid-connected mode and is based on a cyber-physical architecture where smart devices communicate with each other over a secure local network for efficient energy routing, storage, and fault isolation. The semiconductor-based solid state transformer (SST) and fault isolation device (FID) are compact electronic technologies for the future that will lead to highly efficient and intelligent system operation. A distributed intelligence software forms the backbone of the system, and enables these smart devices to exchange information. [45]
5.3.4.2 Reserve capacity microgrids

Yet another game changer in the Smart Grid will be the installation of reserve capacity microgrids—microgrids that can be a source of operating reserve for the grid. As is well-known, the cost of PV solar power has decreased dramatically in the last decade, with both module and nonmodule costs dropping by 40% from 1998 to 2009 [13]. With continuing investment, such as the U.S. Department of Energy’s SunShot initiative, and improved economies of scale as production increases, this trend is likely to continue, if not accelerate. The most obvious consequence is that the life cycle cost of PV solar distributed generation could undercut the cost of centralized generation, paving the way to widespread, ultradense deployment of rooftop grid-connected PV arrays by 2050. Low cost means that entire rooftops could be tiled with PV modules; these arrays might have substantial reserve capacity, so that an array could have a clear-sky capacity exceeding the average consumption of the structure. More broadly, reserve capacity could arise not only from lower per-kilowatt-hour cost at a fixed efficiency, but also from improved PV conversion efficiency and combinations of the two. Ubiquitous deployment of reserve-capacity microgrids will have a profound impact on the operation of next-generation Smart Grid. Reserve capacity could be exploited through module-level dispatch of PV solar power. This approach relies on: 1) modules with <200 W of peak power, and 2) the ability to dispatch their power individually at subsecond timescales. These characteristics, combined with appropriate control algorithms, allow reserve-capacity arrays to be operated at a mean power corresponding to average cloud cover along with high-speed module-level dispatch for high-resolution temporal management of cloud-induced variation. Even more efficient use of reserve capacity might be possible by exploiting geographic diversity through coordination among neighboring microgrids [12].

Indeed, with enough reserve capacity, adaptation to the aggregate variation of generation and consumption could enable grid-level reduction of volatility to levels lower than at present. Consider the example of a neighborhood of single-family homes, each a microgrid unit. With reserve capacity, short-term fluctuation of generation at one unit can be compensated by module-level dispatch at neighboring units. Such a framework can absorb the volatility of other generation sources, such as microwind or combined heat and power plants. Even more gains are possible by joint management of generation and consumption. If a household turns on a 1 kW appliance and its (local) reserve capacity is already allocated for fluctuations in generation, power could be borrowed or purchased from nearby microgrid units in a short-term local market.

Wide-scale, high-density adoption of conventional distributed generation—that is, without management of generation volatility—presents a number of technical challenges centering around stability and safety of the grid at feeder and distribution levels; consequently, achievable adoption levels are often well below 50% [96]. Regulation by rapid dispatch of centralized power (usually fossil-fueled gas turbine generation) could be used for regulation of variation at timescales from roughly 5 seconds to tens of minutes, but this could lead to greater fossil fuel use. Voltage flicker (also known as loss of power quality) can occur at timescales of up to a few seconds, causing volatility at substation and distribution network levels that cannot be compensated by central generation. Further challenges are increased levels of time-varying reactive power and even reverse power flows, which were not anticipated in the design of installed infrastructure.

Reserve capacity in tandem with module-level dispatch provides the tools to directly address these problems. For example, the resulting reduction in volatility implies decreased generation by centralized spinning reserves. By managing power flows within clusters, it also enables maximum use of distributed generation, allowing deferral or even elimination of new centralized generation and transmission infrastructure. Finally, greater distributed generation and microgrids might drive
innovation in the area of low-cost storage technologies that excel at medium-term storage (e.g., for day-night energy transfer).

### 5.3.4.3 Microgrids and storage

Integration and optimal management of storage devices are also important requirements for microgrids. Storage can prevent unstable operation during faults and maintain stability and power quality, especially for islanding and for mitigating load variation and renewable intermittency. The intermittent nature of renewable energy sources demands usage of storage with high energy density; at the same time, rapid fluctuation of load requires that the storage also have high power density. Both requirements can be met with hybrid energy storage systems, although this solution leads to other issues related to their energy management that will need to be addressed [44]. Such a hybrid storage system could, for example, contain both a high energy density storage battery and a high power density storage ultracapacitor. In such a system, the storage energy management system has to allocate steady power demand to the batteries and transient power demand to the ultracapacitor. It needs to increase flexibility in electricity consumption and reduce demand peaks through instruments such as demand-response policies, taking into account the stochastic nature of RES and the imbalance charges due to the mismatch between the actual and the scheduled RES power outputs, considering that the system must operate within its security limits, such as limits on components’ real and reactive powers and line flow limits, and to employ improved forecasts (RES production, demand and energy prices).

### 5.3.5 Virtual power plants and aggregators

With distribution systems containing increasing amounts of electricity production, storage, and communications, we must ultimately ask how and to what end this infrastructure will be coordinated. There are at least two challenges to consider. The first deals with coordinating distribution system resources to manage the local constraints imposed by voltage standards, protection equipment operation, and the durability of mechanical voltage regulating equipment such as OLTCs. The second challenge relates to coordinating aggregation distribution system resources to manage power flow into (or perhaps even out of) distribution substations. This challenge encompasses the first, to the extent that coordinating resources could place additional burdens on distribution system infrastructure. To manage aggregated distribution system resources, one vision is to introduce virtual power plants that manage aggregators in the same way as, for example, traditional CHP units.

### 5.3.5.1 Aggregators

Aggregation systems are a key building block in current and future Smart Grid architectures [93]. The fundamental idea is to harness the value from large numbers of distributed energy resources. A virtual power plant is a managed and controlled collection of distributed generation, consumption, and storage elements that can be represented as a controllable power plant [93]. Along a similar direction, large industrial and commercial loads can be aggregated and their capability can be used for ancillary services. Residential loads have a very large potential for meeting various Smart Grid objectives.
Aggregation systems will require innovative solutions for real-time control of large numbers of distributed energy resources. Key conceptual themes include these examples:

- Measuring and communicating energy states at unit or even subunit levels is unrealistic. However, applying state estimation techniques, energy states at any level of aggregation can be reliably derived based only on temporal and transient load information.

- Disaggregation of distributed energy resources to potentially millions of underlying units should be organized in a hierarchical control system with several layers of aggregation. Controllers at each level will distribute loads (resources) described by macroscopic parameters such as capacity, transient load bounds, price, etc.

- Introducing predictive control action in virtual power plants has the potential of coordinating load distribution on markets with different time horizons in an optimal way. In particular, aggregation based on predictive control has the potential of introducing preemptive action in order to apply virtual storages in an optimal way, as well as to prevent unnecessary congestions.

Challenges

The main challenge in terms of exploiting the full potential of small production units and consuming units is scalability. How can millions of small-scale units be coordinated consistently without an explosion of computational and communications complexity? In principle, aggregation is the answer to just that question. The architectural problems, however, are highly nontrivial and include the following aspects:

- What is the right number of levels of aggregation in order to have the right balance between abstraction and details?

- What is the minimal set of information that can be exchanged between each level? What should be solved by means of measurements and communication and what should be solved by means of estimation techniques?

- How can flexibility best be communicated between levels and what are the right parameters (e.g., maximal/minimal storage, maximum/minimum power rates, price of exploiting flexibility in terms of direct costs, lifetime exhaustion)? An important parameter is probably discomfort, meaning that exploiting flexibility is equivalent to a deviation from the natural or optimal use of a specific system, and that deviation would usually give a deteriorated performance experience for the owner of the unit.

The potential of this approach should be analyzed for realistic scenarios. In particular, the following questions should be addressed:

- What potential is there to operate distribution systems as virtual power plants, which appear to transmission system operators as aggregated resources with the same degree of dispatchability (or more) as large-scale conventional fossil-fueled generators?

- How much PV capacity can a distribution system infrastructure absorb, if electricity storage and reactive power compensation systems are sufficiently well-coordinated?

- Given an understanding of spatio-temporal variation in photovoltaic production and electricity demand, what is the potential to coordinate storage and reactive power compensation systems through decentralized or distributed coordination strategies?
5.3.5.2 Virtual power plants

In current electricity markets, only large or medium-sized producers and trading companies are allowed to act on the major day-ahead markets (e.g., NordPool in northern Europe or EEX in Germany). Small-scale production facilities and consumption only appear in the markets as massively aggregated units. This situation causes the problem that the information needed for small units to enter the spot markets (e.g., Elbas in northern Europe) or markets for control power is lost.

As renewable sources with a high intermittency are increasingly introduced in the power system, the spot markets and the markets for control power will be much more dominating than in the existing system. This domination creates a need for exploiting the large number of small-scale production systems as well as consuming units to offer services in the spot markets and the control power markets. To accommodate this situation, the following changes should be expected or actively pursued:

- A system for dynamic aggregation of a large number of small-scale production units and of consuming units, (i.e., a so-called virtual power plant). The aggregation will depend on the actual role of the small units (e.g., as primary reserves, secondary reserves, balancing, control power market, spot market, etc.).
- A dynamic aggregation depending on the current state of units (Where in their production range are they? which possibilities do they have for stopping production/consumption? what storage capacities do they have?).
- A geographical aspect will also be included in aggregation, so that the configuration will depend on current market boundaries.

Another highly significant challenge relates to how to coordinate and schedule loads, storage, and generators optimally at the level of the transmission system. Factors that can be considered in this scheduling problem include locational marginal price, commitments to provide ancillary services such as frequency regulation and contingency reserves, local transmission-level voltage, reactive power flow, and system frequency. The specific challenges include: 1) energy constraints present in storage and even electricity loads—which might be flexible with respect to their time of operation but are inflexible with respect to the total amount of energy they consume over time, and 2) uncertainty in production from renewable electricity generators and the timing of load operations.

5.3.6 Summary of research challenges

The following is a list of research challenges pertaining to emerging topics in power systems, including electricity markets, demand response, storage, microgrids, and virtual power plants:

1. Representation of the uncertainty in wind energy in market bidding
2. Optimal bidding of independent wind producers into the DAM and building hourly offer curves
3. Hedging mechanisms against liquidity risk, market risks due to volatility, and operational risk due to uncertainty in wind power, unreliable equipment, etc.
4. Optimal penalty costs for deviations in wind production
5. Modeling the impact of intermittency and uncertainty in renewables on ancillary services
6. Integration of suitable demand-response models into both DAMs and RTMs
7. Incorporation of storage and PHEV costs into the market architecture
8. Design of intraday markets and market mechanisms that incorporate some or all of the previous items over a range of timescales
9. The development of dynamic market mechanisms that integrate increasingly accurate forecast models of renewables, consumer behavior, and load control
10. Development of a modeling framework that captures heterogeneous aspects in demand response—startup and shutdown, delays and time constants, and dependencies on environmental factors and among related systems
11. Development of control-oriented reduced order models of wind and solar forecast over a range of time horizons
12. Modeling of decision making of individuals and aggregate entities, including cognitive factors of latency, learning, and fatigue, and behavioral factors of individuals and networks
13. Modeling and design of DR and DSM components so as to enable fast adjustments and realize power balance, and function as a surrogate for ancillary services
14. Coordination of direct load control with price-based demand-response signals, incorporation of multiple time scales, and real and reactive power
15. Determination of when excess power should be generated to feed into storage and when stored energy should be used to help meet demand, while meeting energy and power constraints
16. Coordination of storage in one area with the varying generation in another area resulting in varying tie-line flows with minimal information exchange
17. Adaptive solutions for sudden changes in available storage from electric vehicles
18. Optimal management of interconnected loads and distributed energy resources (including renewables) both in grid-connected and islanded modes
19. Control methods that enable transitions from one operational mode to another in a microgrid while maintaining balances between generation and loads, and thus frequency and voltage control
20. Development of a plug-and-play capability so as to permit a microgrid to be plugged in and out of the legacy grid, as needed
21. Determination of the optimal number of levels of aggregation, the minimal set of information exchange between levels, which leads to a desired balance between abstraction and accuracy
22. Determination of models and parameters that parsimoniously communicate the desired information between levels of decision making
23. Dynamic aggregation of a large number of small-scale production units and of consuming units, that varies with the role of the small units between reserves, capacity, or regulation, or their availability and state
5.4 Loci of control: Grid-wise perspectives

The introduction of new challenges, new components, and new opportunities has paved the way for new perspectives for the power grid. Ensuring the efficiency of the overall grid with the introduction of several heterogeneous components requires fresh approaches. Vulnerabilities introduced due to the insertion of cyber components have to be countered with suitable cyber security measures. Seamless integration with thermal systems for heating and cooling as well as with distributed communication systems is crucial. The role of control in these topics is explored in the following sections.

5.4.1 Energy efficiency

It is well-known that there are very large inefficiencies in the electric energy system. These include losses in the distribution system, losses in end use such as building energy consumption, industrial and manufacturing energy consumption, and electric appliance inefficiencies (see Figure 5.6). There is much potential in reducing waste by using sensing, communications, and control technologies. We discuss, in particular, three different opportunities for control in the following sections.

![Figure 5.6 – End-to-end Electric Power Infrastructure Inefficiencies. From coal to incandescent light bulb, losses as high as 98.4% results. [72]](image)

\[
\text{Overall Efficiency for Converting Chemical Energy To Light Energy} = E_1 \times E_2 \times E_3 = 0.35 \times 0.90 \times 0.05 = 0.016
\]

5.4.1.1 Planning efficiency

A fundamental energy efficiency-related challenge pertains to requirements in the system planning timescale; that is, to plan or to expand the grid infrastructures, over possibly many years, using modern technologies. This goal could be achieved using more efficient power plants, advanced energy storage devices (such as large-scale grid-connected lithium-ion batteries), modern transmission systems, cogeneration plants or combined cooling, heating, and power (CCHP) systems, and more efficient light-emitting diode (LED) and fluorescent lamps. The integration of these technologies will spawn new control challenges. For example, energy storage can significantly improve energy efficiency by enabling control and scheduling of the Smart Grid with a high level of renewable and distributed energy resources. Yet advanced energy storage devices are complex systems, and developing techniques to cost-effectively monitor, manage, and predict important
performance measures is a fundamental challenge. The challenge here is to provide new solutions of original scholarship that avoid the current trend of overdesigning the grid capacities and reserves or operating the grid far below its maximum energy capabilities.

5.4.1.2 Operational efficiency

Another challenge, which can be called *operational efficiency*, pertains to requirements in the system operation timescale; that is, to operate the prevailing set of Smart Grid infrastructures or a subset thereof, over a few-seconds, few-minutes, or few-hours time horizon at higher energy efficiency. For an intuitive understanding of the concept of operational energy efficiency, consider the eight-node electric energy system diagram in Figure 5.7, showing generator (GN), load (LD), line (LN), transformer (TF), and switching device (SW). Assume that all devices were planned and built using the latest energy-efficient technologies. Note that the resistance of the most energy-efficient electric power transmission or distribution line need not vanish, by principles of material science. Also note that operating both lines, LN1 and LN2, during light and heavy load demand periods is well-known to be inefficient, especially for long lines. Clearly, even though all devices are assumed individually energy efficient, it is not hard to see that network switching or reconfiguration, by opening/closing switches, and adjustment of generation and possibly load demand levels, is necessary for increased energy efficiency.

![Figure 5.7 – An eight-node electric energy network](image)

It should be noted that the objective of maximizing operational energy efficiency is not always aligned with that of self-interested agents in a competitive market economy. This coordination problem suffers from partial/incomplete information, illustrated in Figure 5.8, as a two-level decision problem whereby the upper level control system tries to maximize a measure of energy efficiency while generators (GN), consumers (CS), and other self-interested agents (OA) try to maximize their utility function values subject to their respective technical and budget constraints. The control challenge here is therefore to determine a solution that would maximize system- or subsystem-wide operational efficiency while taking account of the strategic gaming from self-interested electric energy agents seeking to maximize their respective utility function values. The underlying issue is one of coordination of self-interested agents, with partial or incomplete information, to reach an overall solution that is most energy efficient.

Typical examples where this objective is relevant is a building-wide or campus-wide coordination of energy consumption with minimal compromise in occupant comfort using occupancy sensors, HVAC models, and coordinated distributed control methodologies.
Figure 5.8 – Illustration of coordinated energy efficiency. Note that \( \mu \) = measure of energy efficiency; \( \pi \) = decision variable of upper level (e.g., price in a competitive environment); \( \hat{x} \) = solution of lower level; \( x_i \) = decision variables of lower level; \( F_i \) = feasible region of decision variables; \( u_i \) = utility function.

5.4.1.3 End-use efficiency

One of the visions of the Smart Grid is to ensure that discrepancy between power produced and power requested is never larger than what can be stored in available storages, even in a society where a large proportion of our present power production has been substituted by a large proportion of renewables.

To makes this equation match, rather than establishing huge storage facilities and excessive numbers of renewable power installations, it could be a more advantageous approach to pursue all ends to reduce consumption of existing facilities. This is especially interesting, where it can be done without vast investments in new technologies and without loss of function of current infrastructures.

The latter is indeed possible by a few cheap enabling technologies combined with advanced control technology. As an example, approximately 55% of the electrical power in the U.S. is used for building comfort systems (residential and commercial). However, recent studies suggest that, on average, the electrical power consumption for a typical HVAC system can be reduced by more than 70%, just by better control algorithms [59].

Similar considerations hold for several other major power consumers such as cold stores, supermarkets, pumping stations, water supply systems, etc.

It should be kept in mind that meeting the power balance better by reducing consumption by 1 GW is in several ways preferable to increasing production by 1 GW. Because this increase can be done to a large extent “simply” by replacing control algorithms, the involved costs are also much smaller in terms of technology that can reduce consumption, compared to technology for increased production.

As sides gain from updating control hardware/software in existing installations, introducing enabling technology for Smart Grid operations can be done at the same time. The installation is thereby transformed into a distributed energy resource in the same operation, through which the owner can sell power services to the grid.
5.4.2 Cyber security

Deployment of Smart Grid technologies raises significant issues regarding security against cyber attacks [23, 54]. Industrial control systems including SCADA networks are known to be vulnerable to cyber attacks [87]. Data from the National Memorial Institute for the Prevention of Terrorism on reported terrorist attacks on the world’s electricity sector from 1994 to 2004 shows that transmission systems are by far the most common target in terms of the total number of physical attacks. Figure 5.9 shows the percentage of terrorist attacks aimed at each of the major grid components.

![Figure 5.9 – Electric terrorism: grid component targets (1994–2004) [22]](image)

5.4.2.1 Layered security

Principles of layered security are eminently applicable to grid cyber security. Layered security (or defense-in-depth) involves strategically combining multiple security technologies at each layer of a computing system, with embedded security, in order to reduce the risk due to the failure of any single security technology. It exponentially increases the cost and difficulty for an attacker to compromise a system by creating a much stronger defense than the use of any individual component alone, thus reducing the likelihood of an attack. A key opportunity in this area is to formulate and optimize the mix and number of layers deployed, while managing risk by minimizing adverse impacts and maximizing return-on-investment (e.g., reducing overall cost of security measures operationally and economically).

5.4.2.2 Deception integrated defense strategy

An additional defense mechanism is the use of deception. Deception consists of two possible techniques: 1) dissimulation (hiding the real data) and 2) simulation (showing the false data).
Deception defense mechanisms can greatly increase the difficulty of planning and conducting successful attacks upon a system by portraying control system response characteristics as random to attackers. They can also alert operators to possible threats before any systems are harmed.

Additional needs include rapid containment, restoration, and recovery strategies that are essential when systems are inevitably compromised. Either software patching or the ability to rapidly identify and isolate the exploited systems must be enabled in order to minimize downtime. This ability is extremely important because the consequences of an attack are directly proportional to the length of time that the service is disrupted.

5.4.2.3 Advanced metering infrastructure

Advanced metering infrastructure (AMI) and smart meters, however, are extremely attractive targets for exploitation, because vulnerabilities can be easily monetized through manipulated energy costs and measurement readings. Such compromised meters can be potentially used to disrupt the load balance of local systems by suddenly increasing or decreasing the demand for power, or by instigating oscillations to destabilize the power system. They can also be exploited to send false control signals, disable grid control center computer systems, disable protective relays, etc.

5.4.2.4 Grid cyber security and control systems research

Cyber security of process control and embedded automation systems, together with the security of the sensors and communication network (at times wireless) are best modeled as automatic control problems [4, 5, 6, 7, 8, 28, 32, 33, 34, 42, 65, 66, 73, 82, 84, 90, 91, 100]. There is significant potential to use tools and techniques from detection and estimation, networked control, and power systems dynamics and control to develop new approaches to cyber security. For example, there has been a flurry of research on the issue of false data injection attacks on power meters in a SCADA system to compromise state estimation, a workhorse of power systems control [31, 49, 52, 63, 89]. Along this direction, it is possible to use power flow equations that encode the basic electric network laws to characterize such attacks. Moreover, it is possible to develop new mitigation schemes using the PMU sensing and communications network.

Cyber attacks that aim to disrupt the stability and performance of the power grid are, obviously, very important. A major challenge here is to model attack vectors as dynamic interventions (malicious disturbances) to the cyber-physical power grid. Observe that unlike pure cyber attacks (e.g., in the banking system), power systems cyber attacks must be in the context of a physical system that is bound to obey laws of power systems networks such as Ohm’s and Kirchhoff’s laws. Now for each cyber-physical attack vector, one can develop detection and mitigations schemes that use the knowledge of the power network, closed-loop control systems, and fundamental known properties and parameters of the physical infrastructure of generators, loads, and network. Work along such directions is now beginning to emerge. There is tremendous potential to develop new cyber-physical-oriented cyber security methods based on such ideas.

5.4.3 Integration with thermal storage

The vision of the Smart Grid includes the potential to systematically exploit flexibility both in producing and consuming (and prosuming) units to allow a much higher penetration of renewable energy resources with a high degree of intermittency in their production. However, independent reports from several continents show that electrical power usage in the range of 20% to 50% from, for example, wind and solar sources, can be achieved only if thermal systems with significant storage
potentials are also incorporated in the overall energy management [27]. Thus, it can be argued that the focus on smart electricity grids is too narrow and that it should be extended to concepts for smart energy grids.

The role of thermal systems in this context is driven by their huge storage capacities and their ability to achieve long-term storage, in the range from hours to days for existing infrastructures, and even exceeding 1 year for future facilities.

The thermal storage potentials vary strongly across the globe and are often correlated with climate. In colder climates, cogeneration (CHP) combined with thermal storages and district-heating systems is an obvious candidate and is already a major energy system component in existing infrastructures at northern latitudes. In warmer climates, similar potentials can be realized based on trigeneration or CCHP—that is, simultaneous generation of electricity and useful heating and cooling from the combustion of a fuel or a solar heat collector, and where the cooling is typically obtained from absorption chillers. In most countries, trigeneration is not yet a widespread technology, but its potential is close to that of cogeneration. Cogeneration and trigeneration are currently linked primarily to fossil and nuclear fuels, but the technology is already being applied to biofuel facilities at a smaller scale. Ultra-long-term thermal storage can be obtained by accumulating heated/cooled water in massive underground storage tanks. The storages can be charged from cogeneration or trigeneration or from huge centralized geothermal heat pumps.

However, for the thermal part of a smart energy grid, optimized management of storage, transmission, and distribution is just as important as for the smart electricity grid. The transformative changes that should be expected or pursued within the next 30 years are as follows:

- Thermal management systems consisting of all thermal producers, consumers, and prosumers, including CHP, CCHP, waste incineration plants, solar thermal energy plants, excess heat from industrial production, bidirectional exchange with buildings, etc.
- Smart energy grids, which manage underlying electrical and thermal grids and their mutual interaction, the latter governed in part by operation of CHP and CCHP and by large-scale heat pumps.
- Establishing thermal storage with long-term storage capacities.

Exploiting thermal storage capacities as a means for mitigating adverse effects of intermittency due to penetration of wind farms and PV plants in the electrical grid necessitates the use of advanced control systems, for the obvious reason that it adds one level of complexity to the management hierarchy in addition to the huge extent of timescales involved. Further, because conversion from electrical to thermal power is (for most practical purposes) unidirectional, it is plausible that model-based control methodologies and control based on predictions will be superior to classical controllers. Specific research challenges from a control perspective include the following examples:

- Design of a control hierarchy for a smart energy grid composed of both electrical and thermal subgrids.
- Design of predictive control algorithms for deciding at the top control level how to convert electrical to thermal energy. This design is highly challenging due to the unidirectional conversion, and would suggest that production and consumption prediction models could improve control performance significantly.
- New models and controls for markets that describe dynamic games, where assets are sold across borders between thermal and electrical systems.
5.4.4 Interplay between communication and control: value of information

Communication systems provide the base infrastructure for reliable operation of power grids. They enable data gathering from all sources and data transmission and distribution to all parties for control, analysis, and information abstraction. The time-critical data from different sources, including the real-time measurements from PMUs, protection IEDs, controllers, PDCs for the transmission and distribution grids, as well as the real-time or time-delayed measurements from the distributed energy resources and end users, have to be quickly and effectively processed into useful information at each level of the system for effective decision making and control in real time.

An important ingredient in the grid architecture is the determination of proper metrics for quantifying reliability. Using proper metrics, one can define a notion of “distance to failure” that can provide an aggregate real-time measure of evolution of a power system towards undesirable states. All such notions need to be efficiently computable from the model and the local observations. Because this measure is global, a certain degree of communication will be necessary to enable its timely computation. The relevant architecture question is thus: What is the proper “degree of decentralization” of communication and computation? An interrelated and important problem in determining the communication and control architecture is quantifying “the value of information.” Given finite resources, not every node in the network will be able to probe/estimate/measure the full model of the system. Such probing is not only expensive, but also leads to accumulations of large amounts of data in the network and thereby creates the undesirable situation of data overload. Developing a systematic approach for quantifying the value of data for each node in the network and rapidly estimating the relevant and actionable information is important, with potentially profound impact on the architecture future power grids.

5.4.5 Summary of research challenges

The following is a list of research challenges for emerging grid-wise perspectives pertaining to efficiency, cyber security, integration with thermal storage, and interplay with communication:

1. Maximization of operational efficiency that accommodates strategic gaming of a range of energy stakeholders in the presence of incomplete information and varied technical and budget constraints (e.g., by making use of coordinated action of multiple agents)
2. Enhancement of end-use efficiency through exploitation of existing storage infrastructure and minimal addition of storage so as to bridge the gap between generation and consumption
3. Modeling of various attack vectors as well as detection and mitigation schemes at all vulnerable points in the grid (e.g., in SCADA)
4. A hierarchical architecture that suitably integrates electrical and thermal subgrids
5. Predictive control at the high level for optimal conversion of electrical to thermal energy
6. Dynamic game theoretic solutions for market strategies that decide asset sales between thermal and electrical systems
7. Determination of the proper degree of decentralization of communication and computation so that the distance to failure is minimized
8. Development of a systematic approach for quantifying the value of data for each node in the network and rapidly estimating the relevant and actionable information
5.5 Loci of control: Game-changing control architectures

The discussions in the previous sections of this chapter suggest a shift of some magnitude in the business-as-usual approach to power grid problems. Here, we address an extreme shift: control-enabled Smart Grid architectures that can be viewed as game changers. Two such architectures are discussed: a grid-wise endpoint control notion and a self-healing grid. Both of these can be viewed as blue-sky visions of Smart Grid in which control is pivotal.

5.5.1 Endpoint control

One possible scenario that the power grid can evolve into is one that consists of millions, possibly billions, of real-time active endpoints with control, outlined in Section 4.2. For this scenario to materialize, we require the deployment of sensors, actuators, and communication devices to be employed en masse, at generators, along transmission lines, at substations, in renewable energy sites, in power-electronic devices, in storage devices and electric vehicles, and in microgrids, buildings, homes, and all smart appliances. This conglomerate entity must evolve according to a tightly coordinated blueprint of closed-loop control that is necessarily implemented in a distributed manner. The following four design principles—with associated challenges for control researchers—are perhaps necessary for the development of a grid-scale endpoint-based control architecture.

5.5.1.1 Control must be real-time and closed-loop

Without uncertainty, we can schedule in advance and fine-tune in real time, as most contemporary engineering and market mechanisms do to match certain supply to predictable demand. With the uncertainty of renewable generation, we must adopt feedback control based on ubiquitous real-time information. The endpoint-based distributed control architecture will combine the advantages of both of today’s main control approaches, by decomposing global objectives into coordinated local algorithms, as shown in Figure 4.2.

5.5.1.2 Algorithms must be scalable

With billions of active endpoints, fast-response sensing and intelligence must be ubiquitous; decisions must be local, but globally coordinated. The architecture must support billions of active endpoints. Algorithms must be decentralized and deployable at a huge distributed scale, adapting on timescales of seconds to minutes.

Algorithm design, be it for Volt/VAR control or real-time pricing, will start with a mathematical model with global objectives. These objectives will then be decomposed into local algorithms for implementation locally at each control point. A decentralized Smart Grid is a multiple-agent system in which each agent makes decisions to optimize its own objective. Design of such algorithms can only be based on solid theoretical foundations and verified using realistic simulations and field trials.

5.5.1.3 Control and economic mechanisms must be jointly designed

Power flow is determined not just by Kirchhoff’s laws, but also by market mechanisms and tariff structures. Its optimization must therefore integrate control and economics. Moreover, market mechanisms are the most successful way to incentivize and organize large distributed control policies. The objectives of all stakeholders are not aligned perfectly, however. We will need to design economic mechanisms and business models to align incentives and market forces to engender desired global outcomes.
5.5.1.4 Cyber security must be built in

The system will require extensive integration of ICT with the power infrastructure from endpoints to distribution and transmission systems. This integration will drastically increase various forms of system vulnerabilities. Smart Grid-specific cyber security measures must be built into the systems or algorithms in the design stage, not retrofitted afterwards.

5.5.1.5 Revisiting mathematical foundations

The theories of control, optimization, and stochastic processes will provide the foundation for a holistic framework that integrates engineering and economics and facilitates systematic algorithm design. One of the biggest challenges with large-scale systems is the difficulty in understanding their structural properties. The interactions between large numbers of local algorithms can often be fragile and cryptic. A successful control and optimization framework will not only lead to local algorithms with high efficiency, but, more importantly, will provide a means to understand their interactions and steer global behavior. Robustness and fragility properties of massively networked systems emerge from the interconnection of local algorithms that are distributed across protocol layers. Often, interesting and counterintuitive behaviors arise when local algorithms interact in intricate ways. Given the scale and diversity of the system, such behaviors will be impossible to discover or explain without a fundamental understanding of the underlying structure. New mathematical frameworks must be developed to explore structures, clarify ideas, and suggest directions to achieve efficient and robust design.

5.5.2 Self-healing grids

An essential ingredient in any critical infrastructure system is its ability to cope with emergent situations. The power grid is no exception to this rule. The Smart Grid, in whatever structure it takes, must possess the ability to respond to disruptions of any and all scales and, simply put, must have the ability to self-heal. When major disruptions occur on a power system today, the transmission network automatically responds by breaking into self-contained islands, according to fixed procedures that have been established well in advance. Such procedures have not generally been updated since the onset of deregulation and will not be adequate for dealing with not only unforeseen causes of nature but also a malicious attack on multiple carefully chosen targets. A game-changing solution could be required, where automatic, self-governed solutions arise in the grid, using a combination of adaptive islanding, raising as many necessary layers of defense, and accelerating recovery after failure. Grouped under the rubric of self-healing grids [3, 5, 7, 8, 9], they pose numerous and formidable challenges for the controls community.

The islanding method must minimize the overall impact of an attack, taking into account the location and severity of damage, load status, and available generation. Such adaptive islanding could be applied either as a precautionary measure to threats detected by intelligence agencies or as a response to sudden, unexpected attacks including severe natural events such as hurricanes.

When failures occur at various locations in such a network, the whole system breaks into isolated islands, each of which must then fend for itself. However, in the proposed Smart Grid, in which the intelligence is distributed throughout the components in the system acting as independent agents, components in each island have the ability to reorganize themselves and make efficient use of available local resources until they are able to rejoin the network. A network of local controllers can act as a parallel, distributed computer, communicating through microwaves, optical cables, or the
power lines themselves, and intelligently limiting their messages to only that information necessary to achieve global optimization and facilitate recovery after failure.

As an example, an event that precipitated the creation of smart self-healing grid foundations was the power outage that cascaded across the western U.S. and Canada on August 10, 1996. This outage began with two relatively minor transmission-line faults in Oregon. But ripple effects from these faults tripped generators at McNary Dam (on the border of Oregon and Washington), producing a 500 MW wave of oscillations on the transmission grid that caused separation of the primary west coast transmission circuit—the Pacific Intertie—at the California/Oregon border. The result: blackouts in 13 U.S. states and Canadian provinces costing some $1.5 billion in damages and lost productivity. Subsequent analysis suggests that shedding (dropping) some 0.4% of the total load on the grid for just 30 minutes would have prevented the cascading effects and prevented large-scale regional outages (note that load shedding is not typically a first option for power grid operators faced with problems).

A necessary feature of a self-healing grid is the presence of multiple modes, during which specific operational and control actions/reactions take place. These modes can ensure a faster than real-time look-ahead simulation and learning loops and become smarter and adaptive to stressors by detecting precursors, predicting attacks, and adapting to disturbances (see Figure 5.11). These modes include the following states:

- **A Normal Mode**, in which an array of sensors monitors the electrical characteristics of the system (voltage, current, frequency, harmonics, etc.) as well as the condition of critical components, such as transformers, feeders, circuit breakers, etc. State and topology estimation will be based on these real-time measurements. The system will constantly be tuning itself to achieve an optimal state based on predetermined optimality criteria, while constantly monitoring for potential problems that could lead to disturbances. When a potential problem is detected and identified, its severity and the resulting consequences will be assessed. Various corrective actions can then be identified, and computer simulations run to study the effectiveness of each action. After the most effective response is determined, a situational analysis will be presented to the operator, who can then implement the corrective action very efficiently by taking advantage of the control system’s automated features.

- **A Disturbance Mode**, in which the system can quickly react to disturbances in such a way as to minimize impact. When an unanticipated disturbance does occur on the system, it will be quickly detected and identified. An intelligent islanding scheme, for example, can be activated automatically to separate the system into self-sustaining parts to maintain electricity supply for customers according to specified priorities, and to prevent blackouts from spreading.

- **A Restorative Mode**, which effectively restores the system to a stable operating region after a disturbance. Following the system’s initial reaction to a disturbance, actions will be taken to move the system towards a stable, optimized operating state. To do so, the status and topology of the system need to be assessed in real time, allowing corrective actions to be identified and their effectiveness to be determined by look-ahead computer simulations. The most effective action can then be implemented automatically. When a stable operating state is achieved, the system will again start to self-optimize.

A clear realization of these modes and mode-transitions can help you realize that the ultimate goal of the smart self-healing grid is to provide automated capabilities that can anticipate and effectively
respond to such events and to other potential problems, to reduce recovery time when unexpected disturbances actually occur and to enhance performance of normal operations.

5.5.3 **Summary of research challenges**

The following is a list of research challenges that emerge with a blue-sky viewpoint based on notions of endpoint control and self-healing:

1. Distributed, real-time closed-loop architectures that accommodate uncertainties in renewable generation and match supply to demand by making use of ubiquitous real-time information, and decomposing global objectives into coordinated local algorithms

2. Scalable algorithms that are decentralized and deployable at a huge distributed scale supported by local decisions and global coordination

3. Integration of economics and distributed control policies to incentivize and align all stakeholders to realize global outcomes

4. Interlacing of grid specific cyber security measures to protect against possible vulnerabilities due to a necessary and extensive introduction of ICT.

5. New mathematical frameworks that combine engineering and economics, control and optimization, and engender robustness of massively networked large-scale systems

6. A multimodal architecture that realizes, distinguishes, and transitions between a normal and emergent state, and launches the corresponding sequence of corrective restorative and healing actions

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**Figure 5.10 – Four states of a power system.** Normal Mode: economic dispatch, load frequency control, maintenance, forecasting, etc. Alert Mode: red flags, precursor detection, reconfiguration and response. Emergency/Disturbance Mode: stability, viability, and integrity – instability, load shedding, etc. Restorative Mode: rescheduling, resynchronization, load restoration, etc.
5.6 Emerging control themes

The foregoing discussion of loci of control and system architectures illuminates some important emerging themes that are likely to be excellent avenues for fundamental advances in control systems and the Smart Grid. These advances are also likely to have applications in other infrastructure systems such as transportation. In this section, we will summarize these emerging themes and game changers.

5.6.1 System of distributed systems

The discussions in the previous sections and chapters indicate that the typical hallmarks of a complex system are available in plenty in the evolution and synthesis of a Smart Grid, ranging from autonomy of varying degrees, emergent subsystems at diverse locations in the grid, cooperative and competitive architectures, self-diagnosing and self-healing subsystems, multiscale dynamics, multicriteria optimization, and a large scale. The combined presence of these complexities with the concomitant needs of honoring constraints of energy balance and capacity at all points of this grid warrants a systematic framework for the analysis and synthesis of a system of distributed systems (Figure 5.11). Each geometric shape in Figure 5.11 represents a class of participant in grid control: 1) round-edge rectangles represent local load control, both residential and small commercial; 2) hexagonal elements represent individual generators or groups of generators at a single facility.

Figure 5.11 – Smart Grid: a system of distributed systems
Groups of these elements participate in higher level grid control through a load aggregator. Several of these work within a control hierarchy. For example, for renewable generation varying stochastically with weather conditions, groups of generators might team up with storage and flexible loads to form a regional collaboration. These are represented by 3) oval figures. Entities in Class 1, Class 2, and Class 3 coordinate their control over a larger geographic area (i.e., style-level in the U.S.) through an area balancing authority. Wide-area supervisory control and wholesale markets will then be coordinated across very large geographic areas (i.e., multiple-state level in the U.S.) by a large entity such as an independent system operator. The bidirectional arrows between these elements represent bidirectional communication that will be required as part of control.

Two main characteristics that pervade this system of distributed systems are that it is: 1) hybrid and 2) hierarchical. Different aspects of the underlying architectures bring in different control challenges and are delineated in the following subsections.

### 5.6.1.1 Hybrid architectures

A common feature among several of the wide-ranging scenarios outlined in Chapter 4 is a hybrid component. Hybrid characteristics of several kinds abound in the electric grid:

- **Distributed + centralized.** A distributed, local, fast-timescale response and action needs to coexist with global, system-based, reliability-driven decision making. The evolution of such architectures and their control in the presence of ubiquitous sensing and sensor-networks, two-way communication networks with distributed yet expertly managed latencies is an emerging theme.

- **Power + communication.** Smart Grid architectures, in all envisioned forms of evolution, are expected to be a hybrid combination of power and communication networks. Efficient realizations of the two, in a hybrid form, that accommodate all necessary constraints of capacity, balance, and latencies are highly desirable.

- **Disparate generation sources.** The combined and necessary presence of varying generation, both in type (fossil fuel/renewable/nuclear), and in size, necessitates the development of suitable frameworks for their efficient use and distribution.

- **System of microgrids.** The theory of systems-of-systems or complex systems has made tremendous progress in the last decade. Control techniques are being developed to deal with these systems, and they will be a useful tool for the optimal management of coordinated microgrids. Considering the hierarchical structure and the self-organizing characteristic needed in microgrids, network optimization and game theory tools would also play a key role in these coordination algorithms. System-wide control objectives can be divided into several distributed controllers, which can be coordinated by means of cooperation based on the interactions between them. Therefore, the complexity of the large-scale Smart Grid can be reduced, also increasing its reliability.

### 5.6.1.2 Distributed architectures

The envisioned Smart Grid will have a very large number of control inputs where it will be necessary to make forward and real-time control decisions at various timescales. These will range from very fast system protection controls, to fast stabilizing feedback control, to wide-area controls, to power generation and consumption decisions with timescales ranging from seconds to hours. These decisions will be necessarily spatially distributed. A ubiquitous feature in these control and decision
problems is that available information for computation of control decisions will be necessarily incomplete. While advanced communications and networking infrastructure will increase the amount of information available in a timely manner, the scale and complexity of the power grid precludes having access to complete information. The other reason for incomplete information is the inherent uncertainties in the system in terms of power generation (renewables), power consumption (uncertain and autonomous loads), and the network (lines, generators, devices experiencing random outages). Thus, it will be necessary to have a suite of tools for control and decision variable computations in the presence of incomplete information. Techniques from stochastic and robust control theories are potentially applicable to such problems. However, it is clear that much additional research will be necessary to identify and develop suitable models, algorithms, and computational processes to yield solutions that can meet the stringent requirements of the smart power grid. Developing fundamental distributed optimization and control concepts that meet these objectives is perhaps one of the most compelling and dominant control themes that is emerging in the Smart Grid area.

The introduction of distributed intelligence in Smart Grid also precipitates challenges in other topics, some of which are as follows:

- **Synchronization and safety.** Transient stability and protection systems are among the fastest subsystems in the power grid. Traditionally, most of such systems use local information and are designed using simple rules and algorithms to ensure safety and stability of the system. Safety issues will become much more important and challenging with the penetration of renewables in the distribution system. On the other hand, the availability of synchrophasor measurements will allow unprecedented levels of real-time state information over large geographical regions of the network. A major challenge will be to compute control decisions for safety and network stability in such situations. A key problem here is to assemble power system (network, dynamics) models fast enough and carry out nonlinear control computations in milliseconds. Such control decisions will need to be robust to modeling (network configuration, dynamic system parameters) uncertainties and information uncertainties. These problems will stimulate new research directions, which will bring together computing, communications, and control with power systems engineering. It is imperative to find effective solutions to these problems to realize the full reliability benefits envisioned from the Smart Grid.

- **State estimation.** Traditional power system state estimation computations are done in a centralized setting in energy management systems. With the advent of Smart Grid capabilities with distributed communications and networks, and new sensors such as synchrophasors, it is natural to develop distributed algorithms for power system state estimation. Recent work has already started to develop such distributed power state estimation algorithms in a Smart Grid context. However, we expect that much further work will be needed to create such distributed state estimation algorithms that can serve the wide variety of needs of the Smart Grid of the future. Application examples include: control distributed renewable generation, demand-response systems, stability and protection systems, failure diagnostics, isolation and recovery systems, etc.

- **Aggregation.** Aggregators represent a new type of entity in the Smart Grid of the future. They are envisioned to use the Smart Grid communications and computational infrastructure and harness the flexibility inherent in distributed generation and consumption to create valuable services for the power system. A simple example is the engineering of demand-response systems to offer the resulting capability as spinning reserves. A related example is management of electric vehicle charging in neighborhoods.
Successful development of such aggregation services will require large-scale distributed communications, computation, and control, and creation of analytic tools that can predict and reliably achieve desired aggregated consumption behaviors. Ultimately, these will be contractual arrangements where the accuracy of the resulting aggregated behavior will be critical, both from engineering as well as economic viewpoints.

5.6.2 Reliability with multiagents

A key expectation from the Smart Grid is the improvement in power system reliability. We expect that new developments in the theory and practice of complex distributed systems will be needed to realize this goal. Although it is easy to foresee the availability of timely information with new sensors, communications, and networks, it is not clear how to extract the benefit from such information. The main challenge arises from the scale, complexity, dynamics, autonomy, and uncertainty of modern power grids. A great example is the Eastern Interconnection of the North American power grid. Even with the availability of Smart Grid infrastructure, it is far from clear today how we will operate the system and avoid large-scale blackouts. Certainly, there are several approaches to realizing such goals. Yet, it is safe to say that new developments in reliability in complex networked uncertain dynamic systems will be necessary to realize the full potential of the Smart Grid.

A specific concept that holds much promise for achieving reliability is that of multiagents. Creating a network of multiagents is one of the most complex tasks facing developers of the power system of the future. They must be simultaneously semiautonomous and collaborative, modular but fully integrated, able to function in multiple modes, and capable of self-improvement based on experience. Figure 5.12 illustrates one architecture that is analytically redundant and hierarchical, and which might be a suitable candidate. This architecture has been validated for sensing and control of high-voltage bulk-power transmission in three major regions in the U.S. as well as in several lower-voltage distribution networks [3, 4, 7, 8].

Figure 5.12 – Real-time learning system architecture: each layer consists of some specialized agents for reacting quickly to changing conditions and others for analyzing conditions based on past experience. These agents can communicate both horizontally and vertically, thus enabling decision making about threats and responses on both local and system-wide levels. [4, 8]
Based on this three-layer structure (deliberative, coordination, and reactive layers), each layer contains a number of agents. The deliberative layer includes agents performing vulnerability assessment, hidden failure monitoring, system reconfiguration, restoration, event identification, and planning tasks. The reactive layer contains the fault isolation and frequency stability agents and the lower level protection and generation agents. The coordination layer agents are event/alarms filtering agents, model update agents, and the command interpretation agents.

Future challenges in this topic include the following examples:

- Ensure the robustness of the software infrastructure using analytically redundant software architecture with two complementary components: a simple and highly reliable core component that guarantees the minimal essential services, and a complex component that provides many desirable features, such as the ability to replace the control agents without the need to shut down and then restart the normal operations. The reliable core will function in spite of failures in the complex component and will provide the state information to restart the complex component should it fail.

- Provide timely and consistent contexts for distributed agents. The stochastic events arising from the dynamics of the system will drive the coordination between distributed agents. An event-driven real-time communication architecture will assemble relevant distributed agents into task-driven teams and will provide the teams with timely and consistent information to carry out coordinated actions.

5.6.3 Control and social sciences: Economics, psychology, and sociology

Yet another emerging theme that Smart Grid systems have ushered in is the integration of control with social sciences such as economics, psychology, and sociology. The role of economics in electric energy systems was elaborated earlier. Although the traditional focus has been on the core transmission grid economics catalyzed by deregulation in the 1990s, new directions for incorporation of ideas from microeconomics will be inspired by new technologies such as demand response, distributed generation, electric vehicles, smart meters, etc. These developments create new questions of suitable models for pricing, efficiency, and distributed decisions by individual economic agents. Economics of distributed networks is an emerging topic where the control community can play a significant role. Given that real-time pricing exhibits substantial geographic and temporal variability, smarter dynamic pricing can be a direct benefit from the evolution of an efficient distributed electricity market. Notions of locational operating reserves have to be rethought in a distributed networks context. Although demand response is an important player that can have a strong impact in the context of distributed networks, care has to be taken to avoid dangers of monopsony.

A key to the successful achievement of Smart Grid goals will be to engage and influence consumer behavior. This is particularly true in demand-response systems. It is critical to understand the role of incentives in successful rollout of demand-response systems. A key feature here is the fact that each individual decision on electric energy consumption might be too small. Also, consumer education on societal issues such as environmental impacts of power generation (e.g., climate change), could have an influence on consumer decisions. There will necessarily be some amount of randomness in such
decisions where segregation of consumer groups could hold great potential. Finally, the role of group membership, community values, and peer relationships is also likely to be quite significant. Insights from psychology and sociology will play an important role in the development of control and information architectures.

5.6.4 Summary of research challenges
The following list includes research challenges that correspond to emerging themes in control theory, including a system of distributed systems, multiple-agent control, and intersections with social sciences:

1. A systematic framework for the analysis and synthesis of a system of distributed systems using a variety of ingredients including cooperative and competitive architectures, self-diagnosing and self-healing subsystems, multiscale dynamics, and multicriteria optimization.

2. Analysis and synthesis of hybrid architectures that combine features of distributed and centralized decisions, power and communication networks, disparate generation sources, and multiple microgrids.

3. Distributed architectures that ensure safety and stability in the presence of incomplete and intermittent information.

4. Development of a multiagent architecture, in which a core component guarantees essential services even during failures, and a complex component enables replacements during transients and restoration without shutdowns.

5. Coordinated multiple-agents who can assemble task-driven teams and provide timely and consistent data based on event-driven communication architectures as well as timely and consistent contexts for distributed agents.

6. Dynamic modeling, mechanisms, and strategies that combine game theory, learning, and adaptation in the face of unknown, irrational, and adversarial market players.

7. Modeling, engaging, and influencing of consumer behavior and synergic interactions between the resulting socio-economic-technical system.

5.7 Concluding remarks
The overarching message in this chapter is that control is everywhere in the emerging cyber-enabled power grid. The need and opportunities for control are plentiful and compelling regarding new designs for transmission and distribution systems to accommodate rapid changes in system conditions and facilitate automated decision making; innovations in market mechanisms, demand response, and storage; and radical architectures of grid-pervasive active endpoint control and central healing. Each of these opportunities is also associated with a host of research challenges that necessitate novel and customized solutions that the controls community is uniquely equipped to provide. It is possible that no single substrate will emerge upon which the requisite control solutions can be built. But it can perhaps be argued that all solutions might need to be distributed, coordinated, and adaptive.

The realization of reliable, green, affordable power can only be made possible by the simultaneous progress in control technologies in several problem domains including market mechanisms, demand response, storage, cyber security, and their integration into the broad grid domains of generation,
transmission, distribution, and end use. These topics are highly interdependent, and, as such, many of the challenges and obstacles might be encountered at the interface.

Collectively, the opportunities that the Smart Grid provides are ushering in new horizons for control. Interdisciplinary research that combines control and social sciences, including economics, sociology, and psychology, is a necessary direction that promises to have a huge impact.

Although all discussions in this chapter and elsewhere in this document pertain to the power grid, they present a blueprint for the control of infrastructure systems in general and can pave the way for control-enabled design and operation of robust, resilient, efficient, and secure complex networked systems such as water, natural gas, and transportation.

5.8 Citations


Chapter 6

Concluding Remarks

A Smart Grid, a cyber-enabled re-envisioning of the end-to-end power system, has the potential to offer tremendous benefits and brings along a number of challenges and opportunities. First we examine the benefits [3]:

- **Sustainability**: A Smart Grid has the potential to achieve a high degree of integration of renewables such as solar, wind, and geothermal energy sources and therefore to play a central role in addressing environmental concerns.

- **Efficiency [4]**: The increased presence of digital technology in a grid, such as AMI, automated demand response combined with dynamic pricing, and enhanced transmission systems with advanced power electronics provides tremendous opportunity for increasing efficiency at several points in the grid including generation, transmission, and distribution.

- **Reliability and security**: A Smart Grid has the ability to reduce wide-area blackouts by anticipating, detecting, and responding to problems rapidly, and to be more resistant to attacks, cyber and otherwise.

- **Improved economy**: As per the Galvin Electricity Initiative [2], Smart Grid technologies have the potential to result in several billion dollars’ worth of savings through a combination of widespread deployment of technology, distributed generation technologies, interactive storage capacity, and savings in infrastructure costs over the next two decades.

- **Affordability**: Affordable energy solutions can be made possible in a Smart Grid by virtue of the grid’s empowered consumers and a cost-effective integration of electric vehicles and other distributed energy resources [1].

Noteworthy is the fact that almost all of the challenges and opportunities in realizing these benefits are control-centric. Whether it is efficiency, reliability, or affordability, control of Smart Grid—the implementation of spatio-temporally orchestrated, affordable, rapid, and universal information transfer between various entities in the grid—can facilitate the realization of these goals. Varied scenarios of a grid with an all-pervasive demand response, a smart periphery with a fully coordinated network of microgrids, a green and automated distribution system, and an efficient AC-DC transmission system might come to fruition by the closing of loops that have not existed or never have been closed before. A multiple-pronged attack with multiple foci of control research is therefore needed, whether they be innovations in the existing systems of generation, transmission, and distribution; the introduction of new concepts of dynamic market mechanisms, demand response, and
microgrid architectures; or an overhaul in the entire grid design motivated by efficiency, self-healing, and cyber security.

Whatever the scenario that reigns at the end, this much is clear: the grid as it exists today is poised for a major transformation, precipitated and spurred on by several reasons, including the following examples:

- Drivers of increasing demand, environmentally friendly energy generation, and empowered consumers are necessitating a new look at the way power is produced and delivered.
- Grid topology is changing. New topologies are necessitating new loops that have never been closed before at new locations and varied instances, using emerging and swiftly varying needs and constraints. Spatio-temporal information transfer (i.e., control) between all actors in the grid has to be carefully orchestrated.
- Commensurate and innovative advances are taking place in the related areas of sensors and actuators—FACTS and PMUs, and responsive, flexible demand response compatible end-use devices.
- Microgrids could be game changers. The currently existing grid could be replaced by a large number of loosely strung microgrids, providing differentiated quality of power based on the needs, resources, and local economy. This scenario might be realized through a fundamental understanding of massively large-scale active endpoint control that collectively optimizes global outcomes through local, cooperative decision making. Self-healing is a necessary and integral part of such a grid.
- The realization of reliable, green, affordable power can only be made possible by the simultaneous progress in control technologies in several problem domains, including market mechanisms, demand response, storage, cyber security, and their integration into the broad grid domains of generation, transmission, distribution, and end-use. Each of these topics is highly interdependent, and as such, many of the challenges and obstacles might be encountered at the interface.
- Heterogeneity could be ubiquitous. It is perhaps not accidental that a wide variety of dissimilar approaches and needs are articulated throughout this document, and that there’s an absence of a one-size-fits-all solution. Different subsystems in the grid have different needs and constraints, necessitating different challenges and correspondingly different control methods. Which specific method is most suited in a specific arena is fodder for research communities to mull over as the years unfold.

Implications of the overall vision presented here and its realization are far reaching. The electric grid is intrinsically connected to other infrastructure systems such as transportation, water, and gas, and public safety and public health. Smart Grid holds significant potential for improving the performance and robustness of these related infrastructure systems.

Cyber-enabled innovations can help revolutionize the power industry much like the telephone industry in the 1980s and the internet in the 2000s. Control is poised to provide a cornerstone in the realization of these innovations. We hope that in the preceding pages, the reader obtained a glimpse of the benefits, challenges, and control opportunities in the grid. We invite the community to embrace this opportunity.
6.1 Citations


