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Multi-Agent System Design Principles for Resilient Operation of Future Power Systems

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***Abstract*—Recently, the academic and industrial literature has coalesced around an enhanced vision of the electric power grid that is intelligent, responsive, dynamic, adaptive and flexible. One particularly emphasized “smart-grid” property is that of resilience where healthy regions of the grid continue to operate while disrupted and perturbed regions bring themselves back to normal operation. Multi-agent systems have recently been proposed as a key enabling technology for such a resilient control scheme. While the power system literature has often addressed multi-agent systems, many of these works did not have resilience as the central design intention. This paper now has a two-fold purpose. First, it seeks to identify a set of multi-agent system design principles for resilient coordination and control of future power systems. To that end, it draws upon an axiomatic design for large flexible engineering systems model which was recently used in the development of resilience measures. From this quantitative model, a set of design principles are easily distilled. Second, the paper assesses the adherence of existing multi-agent system implementations with respect to these design principles. The paper concludes that while many multi-agent systems have been developed for power grids, they have been primarily intended as the decentralization of a particular decision-making/control algorithm. Thus many of the works make only limited contributions to power grid resilience.**

***Index Terms*—power system operation, power system control, power system control hierarchy, multi-agent system, resilience, axiomatic design for large flexible engineering systems,microgrids**

I. Introduction: Resilience in Power System Coordination & Control

Recently, the academic and industrial literature has coalesced around an enhanced vision of the electric power grid that is intelligent, responsive, dynamic, adaptive and flexible [1]–[3]. One particularly emphasized “smart-grid” property is that of resilience where healthy regions of the grid continue to operate while disrupted and perturbed regions bring themselves back to normal operation. This is a cyber-physical grand challenge [4], [5]. It requires a fundamental evolution in the power grid’s physical structure with a corresponding change in the grid’s many layers of control and optimization algorithms [6]. Naturally, these must be considered holistically to achieve the end goal of system resilience.

In regards to the grid’s physical structure, one emerging concept is that of microgrids [7]. These microgrids are defined as electric power systems that: have distributed renewable and thermal energy generation as well as conventional and dispatchable loads. They also have the ability to operate while connected or disconnected from the main power grid [8]–[11]. The high penetration of renewable energy resources introduces new dynamics into these microgrids at all timescales [12], [13]. Furthermore, the introduction of dispatchable energy resources on the demand side suggests an explosion in the number of active devices which require control and coordination [3], [6].

Naturally, a wide array of microgrid literature has emerged to address their control and optimization. Traditional power grid operation and control is a hierarchical structure with three layers [14], [15] that spans multiple power grid timescales. These include a primary and a secondary control and a tertiary dispatch. Many microgrid control and optimization developments have drawn from this traditional hierarchical approach with customizations to account for the unique features found in microgrids [8]–[11]. Generally speaking, each of these layers have typically been addressed individually despite their interdependence. More recent work instead advocates a holistic *enterprise control* approach [6], [16]–[18] where all three layers are simultaneously synthesized, analyzed and simulated.

The microgrid control and optimization developments mentioned above have generally been centralized in nature and thus they have limited resilience with respect to being able to connect and disconnect while certain microgrids are perturbed or disrupted. Furthermore, it is important to consider how multiple microgrids will interact with each other as “peer” regions [19]. Similarly, recent work has advocated resilient control systems [20], [21] built upon open, distributed, and interoperable architectures [4], [5], [22] of the power grid as an integrated cyber-physical system. Multi-agent systems have often been proposed as a key-enabling technology for such a resilient control. The most recent work in this regard is consonant with an enterprise control approach and suggests a hierarchy of agents that address power system management, coordination, and real-time execution control [20], [21].

The application of multi-agent systems in the power systems domain is well-established [23]–[27]. While their original application was often for power system market simulation [28], they have also been used in the context of power system stability control [29]. And yet, the prevailing intention behind these developments is the decentralization of a particular decision-making/control algorithm rather than the development of resilience as a system property. While the former is necessary for the latter, it is far from sufficient.

A. Paper Outline

The purpose of this paper is therefore two-fold. First, it seeks to identify a set of multi-agent system design principles. Second, it assesses the adherence of existing MAS implementations with respect to these design principles. To these ends, the paper is organized as follows. Section IIBackground: Axiomatic Design for Large Flexible Engineering Systems Modelsection.2 presents as background an Axiomatic Design [30] model which was used in the development of resilience measures for large flexible engineering systems. Section IIIDesign Principles for Resilience in Power Systemssection.3 then uses the model to distill a set of MAS design principles that facilitate greater power system resilience. Section IVAdherence of Existing MAS Implementations to Design Principlessection.4 then assesses the adherence of some recent MAS implementations with respect to these design principles. The paper is brought to a conclusion in Section VConclusions & Future Worksection.5.

II. Background: Axiomatic Design for Large Flexible Engineering Systems Model

Recently, a set of resilience measures have been developed for large flexible engineering systems [31], [32]; as a class of systems to which power systems belong.

Definition 1. Large Flexible Engineering System (LFES) [30]: an engineering system with many functional requirements (i.e. system processes) that not only evolve over time, but also can be fulfilled by one or more design parameters (i.e. system resources).

These measures relied on an axiomatic design model [31]–[33] which is summarized here as a collection of definitions upon which the remainder of the discussion is founded. The interested reader is referred to previous works for further discussion and illustrative examples [31]–[38].

At its foundation, Axiomatic Design for Large Flexible Engineering Systems is built upon a mapping of systems processes (P) to system resources (R) [30]–[38]. It takes the form of a design equation

$$P = J_S \odot R \tag{1}$$

where J_S is a binary matrix called a LFES "knowledge base", and $\odot$ is "matrix boolean multiplication".

Definition 2. LFES Knowledge Base [31]–[37]: A binary matrix J_S of size $\sigma(P) \times \sigma(R)$ whose element $J_S(w, v) \in \{0, 1\}$ is equal to one when action $e_{wv} \in E_S$ exists (where $\sigma()$ gives the size of a set).

In other words, the system knowledge base itself forms a bipartite graph which maps the set of system processes to their resources. Each individual mapping represents the existence of a system capability. The system processes and resources may be defined at any level of abstraction and axiomatic design encourages functional and physical decomposition with successive stages of engineering design. As is common in multi-agent system research, the system's processes are defined to include both underlying physical function as well as the supporting enterprise control activities required for their operation [33], [34].

Essential to the development of the model is the specialization of these system processes and resources. The resources $R = M \cup B \cup H$ may be classified into transforming resources $M = \{m_1 \dots m_{\sigma(M)}\}$, independent buffers $B = \{b_1 \dots b_{\sigma(B)}\}$, and transporting resources $H = \{h_1 \dots h_{\sigma(H)}\}$ [31]–[36]. The set of buffers $B_S = M \cup B$ is also introduced for later simplicity. Similarly, the high level system processes are formally classified into three varieties: transformation, transportation and holding processes.

Definition 3. Transformation Process [31]–[36]: A resource-independent, technology-independent process $p_{\mu j} \in P_\mu = \{p_{\mu 1} \dots p_{\mu \sigma(P_\mu)}\}$ that transforms an artifact from one form into another.

Definition 4. Transportation Process [31]–[36]: A resource-independent process $p_{\eta u} \in P_\eta = \{p_{\eta 1} \dots p_{\eta \sigma(P_\eta)}\}$ that transports artifacts from one buffer b_{sy_1} to b_{sy_2}. There are $\sigma^2(B_S)$ such processes of which $\sigma(B_S)$ are "null" processes where no motion occurs. Furthermore, the convention of indices $u = \sigma(B_S)(y_1 - 1) + y_2$ is adopted.

Definition 5. Holding Process [31]–[36]:A transportation independent process $p_{\varphi g} \in P_\varphi$ that holds artifacts during the transportation from one buffer to another.

Example 1. Table IProcesses & Resources in Power Grids as a LFES [31], [32]table.1 provides examples of transformation and transportation processes as well the three types of system resources. Holding processes are often introduced to differentiate between two transportation processes between an origin and a destination. In power grids, they can be used to differentiate transmission lines of different voltage level.

TABLE I
Processes & Resources in Power Grids as a LFES [31], [32]

	P_μ	P_η	M	B	H
Power Grids	Generation/ Consumption	Transmission	Generators/ Loads	Storage	Lines

The distinction between the *existence* and the *availability* of system capabilities is managed by a scleronomic (i.e. sequence-independent) constraints matrix.

Definition 6. LFES Scleronomic Constraints Matrix [31]–[38]: A binary matrix K_S of size $\sigma(P) \times \sigma(R)$ whose element $K_S(w, v) \in \{0, 1\}$ is equal to one when a constraint eliminates event e_{wv} from the event set.

Consequently, a measure of sequence-independent structural degrees of freedom is introduced to measure the number of available system capabilities.

Definition 7. LFES Sequence-Independent Structural Degrees of Freedom [31]–[38]: The set of independent actions E_S that completely defines the available processes in a LFES. Their number is given by:

$$DOF_S = \sigma(E_S) = \sum_{w}^{\sigma(P)} \sum_{v}^{\sigma(R)} \left[J_S \ominus K_S\right](w,v) \tag{2}$$

$$= \langle J_S, \bar{K}_S \rangle_F = tr(J_S^T \bar{K}_S) \tag{3}$$

It is also important to recognize the existence of sequence-dependent (e.g. rheonomic) constraints between structural degrees of freedom.

Definition 8. LFES Rheonomic Constraints Matrix K_ρ [31], [32], [36], [37]: a square binary constraints matrix of size $\sigma(P)\sigma(R) \times \sigma(P)\sigma(R)$ whose elements $K(\psi_1, \psi_2) \in \{0,1\}$ are equal to one when string $z_{\psi 1 \psi 2} = e_{w_1 v_1} e_{w_2 v_2} \in Z$. is eliminated and where $\psi = \sigma(P)(v-1) + w$.

Previous work calculates K_ρ and has shown that it must be non-zero so as to account, at a minimum, for basic rules of continuity. The destination/location of one structural degree of freedom must occur at the origin/location of the subsequent one [31]–[38].

The primary advantage of the axiomatic design model described above is that it is a concise description of system structure.

Definition 9. System Structure [39](page26): the parts of a system and the relationships amongst them. It is described in terms of

- A list of all components (i.e. resources) that comprise it.
- What portion of the total system behavior (i.e. processes) is carried out by each component (i.e. resources).
- How the components (i.e. resources) are interconnected.

On this basis, resilience measures can be formulated as a function of J_S, K_S, and K_ρ.

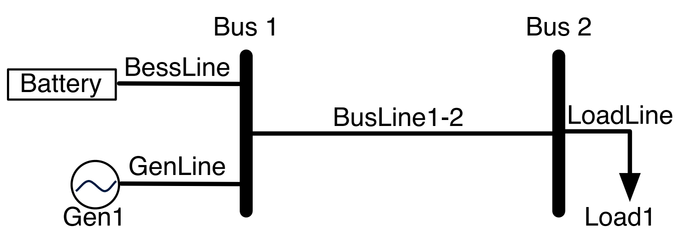

Fig. 1. Example Two-Bus Power System with Generation, Storage and Load

Example 2. Consider the two-bus power system operating at a single voltage of 33kV shown in Figure 1Example Two-Bus Power System with Generation, Storage and Loadfigure.1. M={Gen1, Load1, Battery}. B={Bus1, Bus2}. H={GenLine,LoadLine,BessLine,BusLine1-2}. Note that it is important to include the lead lines to the generator, load and battery as would be done in a transient stability analysis [15]. P_μ={Inject Power, Withdraw Power}. Transportation processes are defined between all possible pairs of independent buffers $B_S = M \cup B$. $J_M = [1, 0, 1; 0, 1, 1]$. J_H^T is compactly drawn as a monochrome image in Figure 2Transpose of Transportation System Knowledge Basefigure.2.

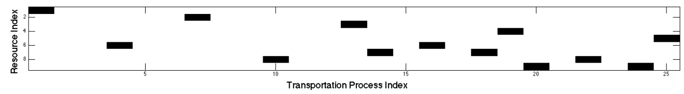

Fig. 2. Transpose of Transportation System Knowledge Base

III. Design Principles for Resilience in Power Systems

The discussion presented in the introduction showed that the resilient coordination and control of future power system must ultimately recognize that the structure of the physical power grid will be in a regular state of change allowing generators, loads and even whole microgrids to connect and disconnect as is necessary in an interoperable fashion. Similarly, the dynamics of the physical power grid and its associated enterprise control will also change. Consequently, any multi-agent system that is implemented as a control system to achieve that resilience must manage both changes in system structure as well as dynamics. On this basis, this work proposes two sets of multi-agent system design principles for 1.) a change of system structure 2.) a change of system dynamics.

A. Design Principles for a Change of System Structure

With the axiomatic design for large flexible engineering systems model in mind, a number of design principles are distilled to account for changes in system structure.

Principle 1. Application of Independence Axiom: The agent architecture must be explicitly described in terms of the power system's structural degrees of freedom.

Principle 2. Existence of Physical Agents: As a decision-making/control system, the multi-agent system must maintain a 1-to-1 relationship with the physical capabilities that exist in the power system.

Principle 3. Functional Heterogeneity: The structural degrees of freedom within the agent architecture must respect the heterogeneity of capabilities found within the power system be they stochastic or deterministic processes or their various types: transformation (i.e. generation, and consumption), transportation (i.e. transmission & distribution) or holding (i.e.storage).

Principle 4. Physical Aggregation: The agent architecture must reflect the physical aggregation of the objects that they represent.

Principle 5. Availability: The agent architecture must explicitly model the potential for sequence independent constraints that impede the *availability* of any given structural degree of freedom.

Principle 6. Interaction: The agent architecture must contain agent interactions along the minimal set of physical sequence-dependent constraints (i.e. nearest neighbor interactions).

Principle 7. Maximum Reconfiguration Potential: Aside from the minimal set of physical sequence-dependent constraints, the agent architecture should avoid introducing any further agent interactions (which may impose further constraints).

Principle 8. Scope of Physical Agents: Agents' scope and boundaries should be aligned with their corresponding physical resources and their associated structural degrees of freedom.

Principle 9. Encapsulation: Power system information should be placed in the agent corresponding to the physical entity that it describes.

Principle 10. Interoperability: Agent-to-Agent interacts should be described by well-known interoperability standards.

The reasoning behind these structural principles is as follows. Because the flow of power can be described as sequences of individual structural degrees of freedom, it is logical to describe the agents in terms of these same structure degrees of freedom (Principle 1principle.1). In Example 2Example.2, individual agents, as a control system, would have to be aware of the power grid's physical activities such as generation, transmission, distribution and consumption. In that regard, structural degrees of freedom are the quantitative equivalent of agent semantic ontologies [40]. The structural degrees of freedom must also be necessary and sufficient; neither overstating nor understating the power system's capabilities (Principles 2principle.2 & 3principle.3). Consider a hypothetical situation in which only some of the structural degrees of freedom in Example 2Example.2 were identified. In such a case, it would be difficult to devise a multi-agent system in which the corresponding resources could be connected, disconnected and actively controlled to achieve resilient operation. Nevertheless, many multi-agent system developments found in the literature do not fulfill Principles 2principle.2 & 3principle.3 because they are focusing on the decentralization of an existing decision-making/control algorithm. For example, an agent-based approach to solving the unit commitment or economic dispatch problem [41] would not require a description of the power grid topology and its associated structural degrees of freedom. The agents must also have a level of aggregation that mimics that of the physical entities that they represent (Principle 4principle.4). Reconsider Example 2Example.2 as a two-area transmission system with the traditional case that the load represents a full distribution system utility. Principle 4principle.4 would require that this "load" now be represented as an aggregated set of resources which cooperate to behave as a net-load on the transmission system. Next, the agent architecture must distinguish between the existence and availability of its capabilities (Principle 5principle.5). This principle is essential for resilient operation where any given resource can be taken on or offline. The existence of sequence-dependent constraints in the physical power grid suggests for the need for the same amongst the agents (Principle 6principle.6). Reconsider Example 2Example.2. The generator, storage, and load units need to know their relative proximity to the transmission line that connects them. Next, adding agent interactions beyond the ones on the physical power grid is likely to introduce additional constraints that might limit their ability to dynamically connect and disconnect (Principle 7principle.7). Principle 8principle.8 ensures that when a reconfiguration process occurs (i.e. addition, modification or removal of a structural degree of freedom), it does so simultaneously on the physical resource as well as on the corresponding agent. Previous reconfigurability measurement work has shown that in many cases misaligned informatic entities such as centralized controllers lead to greater coupling of structural degrees of freedom [42]; thus hindering ease of reconfiguration. Recent work in power system state estimation has recognized the challenge of gathering geographically dispersed measurements from a variable power grid topology; thus motivating recent developments in distributed state estimation [43]. Principles 7principle.7 & 9principle.9 recognize that information is more often used locally rather than remotely and thus encourages greater encapsulation and modularity. Finally, Prinicple 10principle.10 encourages the use of multi-agent system standards such as FIPA [44] and IEC61499 [45].

B. Design Principles for a Change of System Dynamics

In addition to the design principles for a change of system structure, it is necessary to identify the same for a change of system dynamics taking into consideration the full set of power grid enterprise control activities.

Principle 11. Scope of Physical System Model & Decision Making: The physical system model must describe the physical system behavior at all time scales for which resilient decision-making/control is required. These time scales are described by characteristic frequencies for continuous dynamics and characteristic times for discrete (pseudo-steady-state) processes.

Principle 12. Temporal Scope of Execution Agent/Real-time Controller: The characteristic frequencies in the physical system model must be controlled by at least one execution agent/real-time controller capable of making decisions 5x faster than the fastest characteristic frequency.

Principle 13. Temporal Scope of Coordination Agent: A coordination agent may not take decisions any faster than 5x slower than the slowest characteristic frequency in the physical system model.

Principle 14. Equivalence of Agent Hierarchy & Time Scale Separation: If the physical system model has two or more characteristic frequencies or times that are (mathematically proven or practically assumed to be) independent then the associated agent may be divided into an equal number of hierarchical agents each responsible for decision-making/control for the associated characteristic frequency or time.

The reasoning behind these dynamic principles is as follows. Principle 11principle.11 recognizes that the multi-agent system is part of a larger cyber-physical system. Therefore, it will either have a virtual model of the physical system or it will connect to such a model during the engineering design and testing. In either case, such a model must be rich enough to include all of the physical phenomena relevant to resilient operation. For example, the unit commitment problem must account for startup/shutdown times and load/generator ramp rates [15]. Meanwhile, dynamic reconfiguration of multiple microgrids implies a full transient-stability model of the power grid [15]. Principle 11principle.11 also implies two types of agents; those responsible for executing real-time dynamics and those responsible for pseudo-state coordination. This is consonant with recent works on resilient control systems [20], [21]. To avoid mathematical convolution, real-time execution agents/controllers must operate at a time-scale significantly faster than the dynamics that they control (Principle 12principle.12). This principle can impose a strict real-time requirement. In the case of switching decisions between multiple microgrids, dynamics can be on the order of $100ms$. Principle 13principle.13 is also based upon the avoidance of mathematical convolution. Furthermore, dynamic instability can arise if Principle 13principle.13 is violated. Principle 14principle.14 recognizes that different power system phenomena either are, or can be assumed to be, effectively decoupled in time and the agent hierarchy can be designed accordingly. For example, unit commitment and economic dispatch problems are usually time scale separated [15]. Additionally, small-signal stability dynamics are often categorized as intra-area and inter-area dynamics [46].

IV. Adherence of Existing MAS Implementations to Design Principles

With these multi-agent system design principles identified, the discussion can turn to evaluating the existing multi-agent system power grid literature. The evaluation was conducted on power grid multi-agent systems that 1.) are published after 2010 and 2.) include a control system composed of multiple agents 3.) demonstrate closed-loop control of a simulation model or physical hardware. This lead to the inclusion of Refs. [47]–[57]. Figure 3Adherence of Existing MAS Implementations to Design Principlesfigure.3 shows the results of the assessment where green, yellow and red corresponding to full, partial and non-adherence to the MAS design principles.

The results of the assessment suggest that MAS development for power grids has been primarily intended as the decentralization of a particular decision-making/control algorithm rather than the development of resilience as a system property. The most common of these decisions may be broadly categorized as either energy management or fault location, isolation, and supply restoration (FLISR). The former often neglected the power grid topology, while the latter often neglected some type of energy resource. Furthermore, most of the the works did not strictly adhere to the principles of physical agency. These observations naturally meant that the availability of all physical resources was often partial. Only the work of Rivera et al. [56], [57][1] fully adhered to Principles 1principle.1, 2principle.2, 3principle.3, 5principle.5 & 8principle.8. The literature as a whole was found to be weak with respect to physical aggregation (Principle 4principle.4). Either aggregation was not addressed, or it lead to centralized-decision-making algorithms. In the latter case, this consequently leads to additional agent-to-agent interactions and compromised encapsulation (Principles 7principle.7 & 9principle.9). The literature as a whole was also found to be weak with respect to physical nearest-neighbour interactions (Principle 6principle.6). A MAS implementation that does not fully describe the system's structural degrees of freedom will naturally neglect the interactions between them. That said, one nearly universal strength of the literature was its utilization of interoperability standards such as FIPA-compliant agents, IEC61499, and IEC61850 (Principle 10principle.10).

The multi-agent system implementations considered in the assessment were generally well suited to changes in power system dynamics at the various time-scales of enterprise control. While all considered works included either a physical grid simulation model or physical hardware, some did not describe the specifics of the implementation leading to questions of their suitability (Principle 11principle.11). Almost all works addressed coordination decisions as a pseudo-steady-state process (Principle 13principle.13) while others addressed power grid dynamics with real-time execution agents/controllers (Principle 12principle.12). For those implementations that considered both time scales, an agent hierarchy composed of at least two layers consequently emerged (Principle 14principle.14).

V. Conclusions & Future Work

This paper has identified a set of multi-agent system design principles for the resilient coordination and control of future power systems. To that effect, it drew upon an axiomatic design for large flexible engineering systems model that has been used in the development of resilience measures. The newly identified MAS design principles were then used to evaluate the adherence of some recent MAS power grid implementations. The results of the assessment suggest that MAS development for power grids has been primarily intended as the decentralization of a particular decision-making/control algorithm rather than the development of resilience as a system property. While the former is necessary for the latter, it is far from sufficient. In the future, the authors hope to apply these design principles to achieve greater resilience in MAS implementations applied in the power grid domain.

References

[1] J. G. Kassakian, R. Schmalensee, G. Desgroseilliers, T. D. Heidel, K. Afridi, A. M. Farid, J. M. Grochow, W. W. Hogan, H. D. Jacoby, J. L. Kirtley, H. G. Michaels, I. Perez-Arriaga, D. J. Perreault, N. L. Rose, G. L. Wilson, N. Abudaldah, M. Chen, P. E. Donohoo, S. J. Gunter,

[1] While such a conclusion may seem subjective, it must be disclosed that the design of this MAS implementation was occurring at the same time that the authors were developing the theory of resilience measurement. Naturally, this caused a constructive feedback loop between the two research activities.

	[47,48]	[49]	[50,51]	[52]	[53]	[54]	[55]	[56,57]
1	Model limited to lines & substations. No model for power generation & consumption.	Model limited to power generation, consumption & storage. No agents assigned to grid topology.	Model limited to power generation, consumption & storage. No agents assigned to grid topology.	Model limited to power generation, consumption & storage. No agents assigned to grid topology.	Model limited to power generation, consumption & storage. No agents assigned to grid topology.	Model limited to power generation, consumption, and lines. No agents assigned to buses, storage, RE, or dispatchable load.	Model limited to load and bus agents.	Model addresses all power system structural degrees of freedom.
2	One physical resource has many function blocks. Each function block is meant to be part of a larger control agent.	Each agent has a physical resource. Not all physical resources have an agent.	Some physical agents are included. Some centralized agents are included. No agents assigned to grid topology.	Some physical agents are included. Some centralized agents are included. No agents assigned to grid topology.	Each agent has a physical resources. No agents are assigned to grid topology.	Some physical agents are included. Some centralized agents are included.	Some physical agents are included. Some centralized agents are included.	1-to-1 relationship of physcial agents to resources.
3	Model limited to lines & substations. No model for power generation & consumption.	Model limited to power generation, consumption & sotrage. No agents assigned to grid topology.	Model limited to power generation, consumption & sotrage. No agents assigned to grid topology.	Model limited to power generation, consumption & storage. No agents assigned to grid topology.	Model limited to power generation, consumption & storage. No agents assigned to grid topology.	Model limited to power generation, consumption, and lines. No agents assigned to buses, storage, RE, or dispatchable load.	Model limited to load and bus agents.	Model addresses all power system structural degrees of freedom.
4	Does not address the aggregation of generators, loads, or power grid areas.	A grid agent is included as a single entity rather than an aggregation of multiple entities.	A microgrid manager agent is included as a centralized decision-making entity.	Centralized agents are included for centralized decision-making.	Does not address the aggregation of generators, loads, or power grid areas.	Centralized agents are included for centralized decision-making.	Centralized agents are included for centralized decision-making.	Centralized agents are included for centralized decision-making.
5	Only Line & substation availability. Generation/Consumption not included.	All agents are assumed to be online.	All agents are assumed to be online. Microgrid can operate in grid-connected and disconnected modes.	All agents are assumed to be online.	All agents are assumed to be online.	All agents except for central agent & grid agent can be unavailable.	Only Line & substation availability. Generation/Consumption not included.	All agents can be switched on/off.
6	Function block interactions exists between lines & substations but not with generation & loads.	Without agents assigned to the topology agents, there can be no coordination between energy and topology elements or between topology elements.	Without agents assigned to the topology agents, there can be no coordination between energy and topology elements or between topology elements.	Without agents assigned to the topology agents, there can be no coordination between energy and topology elements or between topology elements.	Without agents assigned to the topology agents, there can be no coordination between energy and topology elements or between topology elements.	Without agents assigned to buses, storage, RE and dispatchable loads, coordination decisions are limited.	Without agents assigned to other physical resources, coordinated decisions are limited.	Agent architecture does not include interaction between branches, buseses & energy elements.
7	No extraneous agent interactions have been added.	Supercondensator initiates all negotiations with other agents in a sequential fashion.	Introduction of multiple centralized decision-making agents likely to add extra agent-to-agent communication	Introduction of multiple centralized decision-making agents likely to add extra agent-to-agent communication	No extraneous agent interactions have been added.	Introduction of multiple centralized decision-making agents likely to add extra agent-to-agent communication	Facilitator acts as a centralized agent.	Introduction of centralized decision-making agent likely to add extra agent-to-agent communication
8	1-many cyber-physical relation but each function block is meant to be an automation object as part of a larger control agent.	Agents are assigned to PV, storage, and external grid. No agents for loads, lines, and substations.	Some physical agents are included. Some centralized agents are included. No agents assigned to grid topology.	Some physical agents are included. Some centralized agents are included. No agents assigned to grid topology.	Each agent has a physical resources. No agents are assigned to grid topology.	Some physical agents are included. Some centralized agents are included.	Some physical agents are included. Some centralized agents are included.	1-to-1 relationship of physcial agents to resources.
9	Fulfilled.	Fulfilled.	The use of centralized decision-making causes local information to be centralized.	The use of centralized decision-making causes local information to be centralized.	Fulfilled.	The use of centralized decision-making causes local information to be centralized.	The use of centralized decision-making causes local information to be centralized.	The use of centralized decision-making causes local information to be centralized.
10	IEC61850/61499 are used with function blocks. Does not consider FIPA-compliant agents.	Matlab simevents is used for the development of MAS. Not FIPA compliant.	FIPA Compliant JADE Agents	FIPA Compliant JADE Agents	FIPA Compliant JADE Agents	Matlab is used for the development of MAS. Not FIPA compliant.	FIPA Compliant JADE Agents	FIPA Compliant JADE Agents
11	SimPower Systems Model but specifics are not mentioned.	Physical model of a DC grid implemented in simulink.	Real-Time Digital Simulator/Power World Simulator as physical model.	Small-signal stability model implemented in Matlab.	Real-time diesel generator included.	Physical model of system implemented in Matlab	Physical system model of implemented in Matlab/Simulink w/o specifices.	Transient stability physical model implemented in Matlab.
12	Function blocks are intended as real-time execution agent for fast switching decisions.	None present.	None present.	f-V and P-Q controls implemented as real-time execution agents.	Governor control implemented as real-time execution agent.	Voltage and PQ control implemented as real-time execution agents.	None present.	Automatic Generation Control & Automatic Voltage Regulators implemented real-time execution agents.
13	Slower timescales are not considered	Coordination agents address energy-management functionality.	Coordination agents address energy-management functionality.	Middle level coordination and high level energy management agents address balancing and voltage control operation	Coordination agents address energy-management functionality.	Central agent address black start service.	Central agent addresses restoration service.	Coordination agents address energy-management functionality.
14	Since only one time scale is considered, function-block layer is flat.	Since only one time scale is considered, agent architecture is flat.	Energy management is considered for the day-ahead and real-time markets. Power grid dynamics are not.	Three layer agent hierarchy devoted real-time frequency control, voltage coordination and energy management.	Two layer control hierarchy: energy management & real-time frequency control.	Two layer control hierarchy: black start coordination & real-time control.	Since only one time scale is considered, function-block layer is flat.	Two layer control hierarchy: energy management & real-time control.
Decision	Fault Location, Isolation & Supply Restoration	Energy management	Energy management	Energy management, voltage control, small-signal stability	Energy management & Frequency Control	Black start coordination & Real-Time Control	Restoration Service	Energy management & Frequency Control
Implementation	IEC61499 Function Block Implementation w/ SimPower Systems Simulation	Matlab Simevents/Simulink Implementation	JADE Agents with Real Time-Digital Simulator/Power World Simulator	JADE Agents with Small-Signal Stability Matlab Simulator	JADE Agents with Real-Time JAVA simulation	Matlab Implementation	JADE Agents with Simulink/Matlab Simulator	JADE Agents with Transient Stability Matlab Simulator

Fig. 3. Adherence of Existing MAS Implementations to Design Principles

P. J. Kwok, V. A. Sakhrani, J. Wang, A. Whitaker, X. L. Yap, R. Y. Zhang, and M. I. of Technology, *The Future of the Electric Grid: An Interdisciplinary MIT Study*. Cambridge, MA: MIT Press, 2011.

[2] S. M. Amin, "Smart grid Overview issues and opportunities. Advances and challenges in sensing modeling simulation optimization and control," *European Journal of Control*, vol. 17, no. 5-6, pp. 547–567, 2011.

[3] A. M. Annaswamy, M. Amin, C. L. Demarco, and T. Samad, Eds., *IEEE Vision for Smart Grid Controls: 2030 and Beyond*. New York NY: IEEE Standards Association, 2013.

[4] M. D. Ilic, "From Hierarchical to Open Access Electric Power Systems," *Proceedings of the IEEE*, vol. 95, no. 5, pp. 1060–1084, May 2007.

[5] M. D. Ilic, L. Xie, U. A. Khan, and J. M. F. Moura, "Modeling of Future Cyber-Physical Energy Systems for Distributed Sensing and Control," *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on*, vol. 40, no. 4, pp. 825–838, 2010.

[6] A. M. Farid and A. Muzhikyan, "The Need for Holistic Assessment

Methods for the Future Electricity Grid," in *GCC CIGRE Power 2013*, Abu Dhabi, UAE, 2013, pp. 1–12.
[7] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay, "Microgrids," *IEEE Power and Energy Magazine*, vol. 5, no. 4, pp. 78–94, 2007.
[8] A. Bidram and A. Davoudi, "Hierarchical Structure of Microgrids Control System," *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 1963–1976, Dec. 2012.
[9] R. Majumder, "Some Aspects of Stability in Microgrids," *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 3243–3252, Aug. 2013.
[10] J. M. Guerrero, P. C. Loh, T.-L. Lee, and M. Chandorkar, "Advanced Control Architectures for Intelligent Microgrids-Part II: Power Quality, Energy Storage, and AC/DC Microgrids," *Industrial Electronics, IEEE Transactions on*, vol. 60, no. 4, pp. 1263–1270, 2013.
[11] J. M. Guerrero, M. Chandorkar, T. Lee, and P. C. Loh, "Advanced Control Architectures for Intelligent Microgrids—Part I: Decentralized and Hierarchical Control," *Industrial Electronics, IEEE Transactions on*, vol. 60, no. 4, pp. 1254–1262, 2013.
[12] J. Apt, "The spectrum of power from wind turbines," *Journal of Power Sources*, vol. 169, no. 2, pp. 369–374, Jun. 2007.
[13] A. E. Curtright and J. Apt, "The character of power output from utility-scale photovoltaic systems," *Progress in Photovoltaics: Research and Applications*, vol. 16, no. 3, pp. 241–247, May 2008.
[14] A. J. Wood and B. F. Wollenberg, *Power generation, operation, and control*, 3rd ed. Hoboken, NJ, USA: John Wiley & Sons, 2014.
[15] A. Gomez Exposito, A. J. Conejo, C. Canizares, A. Gómez-Expósito, and C. Cañizares, *Electric energy systems: analysis and operation*. Boca Raton, Fla: CRC, 2008, vol. The electr, no. Recommended.
[16] A. M. Farid, "Holistic Assessment for Enterprise Control of the Future Electricity Grid," *IEEE Smart Grid Newsletter*, vol. September, pp. 1–3, 2013.
[17] A. Muzhikyan, A. M. Farid, and K. Youcef-Toumi, "Variable Energy Resource Induced Power System Imbalances: Mitigation by Increased System Flexibility, Spinning Reserves and Regulation," in *IEEE Conference on Technologies for Sustainability*, Portland, Oregon, 2013, pp. 1–7.
[18] ——, "Variable Energy Resource Induced Power System Imbalances: A Generalized Assessment Approach," in *IEEE Conference on Technologies for Sustainability*, Portland, Oregon, 2013, pp. 1–8.
[19] R. H. Lasseter, "Smart Distribution: Coupled Microgrids," *Proceedings of the IEEE*, vol. 99, no. 6, pp. 1074–1082, Jun. 2011.
[20] C. G. Rieger, K. L. Moore, and T. L. Baldwin, "Resilient Control Systems: A multi-agent dynamic systems perspective," in *2013 IEEE International Conference on Electro/Information Technology (EIT)*, 2013, pp. 1–16.
[21] C. Rieger and Q. Zhu, "A hierarchical multi-agent dynamical system architecture for resilient control systems," in *2013 6th International Symposium on Resilient Control Systems (ISRCS)*. Ieee, Aug. 2013, pp. 6–12.
[22] A. Vaccaro, M. Popov, D. Villacci, and V. Terzija, "An Integrated Framework for Smart Microgrids Modeling, Monitoring, Control, Communication, and Verification," *Proceedings of the IEEE*, vol. 99, no. 1, pp. 119–132, Jan. 2011.
[23] S. D. J. McArthur, E. M. Davidson, V. M. Catterson, A. L. Dimeas, N. D. Hatziargyriou, F. Ponci, and T. Funabashi, "Multi-Agent Systems for Power Engineering Applications—Part I: Concepts, Approaches, and Technical Challenges," *Power Systems, IEEE Transactions on*, vol. 22, no. 4, pp. 1743–1752, 2007.
[24] ——, "Multi-Agent Systems for Power Engineering Applications; Part II: Technologies, Standards, and Tools for Building Multi-agent Systems," *Power Systems, IEEE Transactions on*, vol. 22, no. 4, pp. 1753–1759, 2007.
[25] R. Roche, B. Blunier, A. Miraoui, V. Hilaire, and A. Koukam, "Multi-agent systems for grid energy management: A short review," in *IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society*, 2010, pp. 3341–3346.
[26] A. A. L. Dimeas, S. S. Member, and N. D. N. Hatziargyriou, "Operation of a Multiagent System for Microgrid Control," *IEEE Transactions on Power Systems*, vol. 20, no. 3, pp. 1447–1455, Aug. 2005.
[27] M. Glavic, "Agents and Multi-Agent Systems : A Short Introduction for Power Engineers," Tech. Rep., 2006.
[28] M. Shahidehpour, H. Yamin, and Z. Y. Li, *Market Operations in Electric Power Systems*. New York, New York, USA: New York: Wiley, 2002.
[29] H. Ni, G. T. Heydt, and L. Mili, "Power system stability agents using robust wide area control," pp. 1123–1131, 2002.
[30] N. P. Suh, *Axiomatic Design: Advances and Applications*. Oxford University Press, 2001.
[31] A. M. Farid, "Static Resilience of Large Flexible Engineering Systems : Part I – Axiomatic Design Model," in *4th International Engineering Systems Symposium*, Hoboken, N.J., 2014, pp. 1–8.
[32] ——, "Static Resilience of Large Flexible Engineering Systems : Part II – Axiomatic Design Measures," in *4th International Engineering Systems Symposium*, Hoboken, N.J., 2014, pp. 1–8.
[33] A. M. Farid and D. C. McFarlane, "Production degrees of freedom as manufacturing system reconfiguration potential measures," *Proceedings of the Institution of Mechanical Engineers, Part B (Journal of Engineering Manufacture)*, vol. 222, no. B10, pp. 1301–1314, Oct. 2008.
[34] A. M. Farid, "Reconfigurability Measurement in Automated Manufacturing Systems," Ph.D. Dissertation, University of Cambridge Engineering Department Institute for Manufacturing, 2007.
[35] ——, "Product Degrees of Freedom as Manufacturing System Reconfiguration Potential Measures," *International Transactions on Systems Science and Applications*, vol. 4, no. 3, pp. 227–242, 2008.
[36] ——, "An Axiomatic Design Approach to Non-Assembled Production Path Enumeration in Reconfigurable Manufacturing Systems," in *2013 IEEE International Conference on Systems Man and Cybernetics*, Manchester, UK, 2013, pp. 1–8.
[37] A. Viswanath, E. E. S. Baca, and A. M. Farid, "An Axiomatic Design Approach to Passenger Itinerary Enumeration in Reconfigurable Transportation Systems," *IEEE Transactions on Intelligent Transportation Systems*, vol. PP, no. 99, pp. 1–10, 2013.
[38] E. E. S. Baca, A. M. Farid, and I.-T. Tsai, "An Axiomatic Design Approach to Passenger Itinerary Enumeration in Reconfigurable Transportation Systems," in *Proceedings of ICAD2013 The Seventh International Conference on Axiomatic Design*, Worcester, MA, USA, 2013, pp. 138–145.
[39] D. W. Oliver, T. P. Kelliher, and J. G. Keegan, *Engineering complex systems with models and objects*. New York: McGraw-Hill, 1997.
[40] D. Gasevic, D. Djuric, and V. Devedzic, *Model driven engineering and ontology development*, 2nd ed. Dordrecht: Springer, 2009.
[41] D. Sharma, A. Trivedi, D. Srinivasan, and L. Thillainathan, "Multi-agent modeling for solving profit based unit commitment problem," *Applied Soft Computing Journal*, vol. 13, no. 8, pp. 3751–3761, 2013.
[42] A. M. Farid, "Facilitating ease of system reconfiguration through measures of manufacturing modularity," *Proceedings of the Institution of Mechanical Engineers, Part B (Journal of Engineering Manufacture)*, vol. 222, no. B10, pp. 1275–1288, 2008.
[43] A. Gomez-Exposito, A. de la Villa Jaen, C. Gomez-Quiles, P. Rousseaux, and T. Van Cutsem, "A taxonomy of multi-area state estimation methods," *Electric Power Systems Research*, vol. 81, no. 4, pp. 1060–1069, 2011.
[44] S. Poslad, "Specifying protocols for multi-agent systems interaction," *ACM Transactions on Autonomous and Adaptive Systems*, vol. 2, no. 4, pp. 15–es, Nov. 2007.
[45] V. Vyatkin, *IEC 61499 Function Blocks for Embedded and Distributed Control Systems*. Research Triangle Park, NC, USA: Instrumentation Society of America, 2007.
[46] P. Kundur, *Power system stability and control*. McGraw-Hill, 1994.
[47] G. Zhabelova and V. Vyatkin, "Multiagent Smart Grid Automation Architecture Based on IEC 61850/61499 Intelligent Logical Nodes," pp. 2351–2362, 2012.
[48] N. Higgins, V. Vyatkin, N. Nair, and K. Schwarz, "Distributed Power System Automation With IEC 61850 , IEC 61499, and Intelligent Control," *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews*, vol. 41, no. 1, pp. 81–92, 2011.
[49] J. Lagorse, D. Paire, and A. Miraoui, "A multi-agent system for energy management of distributed power sources," *Renewable Energy*, vol. 35, no. 1, pp. 174–182, Jan. 2010.
[50] T. Logenthiran, D. Srinivasan, A. M. Khambadkone, and H. N. Aung, "Multiagent System for Real-Time Operation of a Microgrid in Real-Time Digital Simulator," *Smart Grid, IEEE Transactions on*, vol. 3, no. 2, pp. 925–933, 2012.
[51] T. Logenthiran and D. Srinivasan, "Multi-agent system for the operation of an integrated microgrid," *Journal of Renewable and Sustainable Energy*, vol. 4, no. 1, p. 013116 (20 pp.), Jan. 2012.
[52] C.-X. Dou and B. Liu, "Multi-Agent Based Hierarchical Hybrid Control for Smart Microgrid," *IEEE Transactions on Smart Grid*, vol. 4, no. 2, pp. 771–778, 2013.

[53] C. M. Colson and M. H. Nehrir, "Comprehensive Real-Time Microgrid Power Management and Control With Distributed Agents," *IEEE Transactions on Smart Grid*, vol. 4, no. 1, pp. 617–627, Mar. 2013.

[54] N. Cai, X. Xu, and J. Mitra, "A hierarchical multi-agent control scheme for a black start-capable microgrid," in *Power and Energy Society General Meeting, 2011 IEEE*, 2011, pp. 1–7.

[55] W. Khamphanchai, S. Pisanupoj, W. Ongsakul, and M. Pipattanasomporn, "A multi-agent based power system restoration approach in distributed smart grid," pp. 1–7, 2011.

[56] S. Rivera, A. M. Farid, and K. Youcef-Toumi, "A Multi-Agent System Coordination Approach for Resilient Self-Healing Operation of Multiple Microgrids," in *Industrial Agents: Emerging Applications of Software Agents in Industry*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2014, ch. 1, pp. 1–20.

[57] ——, "A Multi-Agent System Transient Stability Platform for Resilient Self-Healing Operation of Multiple Microgrids," in *5th Innovative Smart Grid Technologies Conference*, Washington D.C., 2014, pp. 1–5.