Relative Merits of Load Following Reserves & Energy Storage Market Integration Towards Power System Imbalances

Aramazd Muzhikyan, Amro M. Farid, Kamal Youcef-Toumi

Abstract

Traditionally, power system balancing operations consist of three consecutive control techniques, namely security-constrained unit commitment (SCUC), security-constrained economic dispatch (SCED), and automatic generation control (AGC). Each of these have their corresponding type of operating reserves. Similarly, energy storage resources (ESRs) may be integrated as energy, load following, or regulation resources. A review of the existing literature shows that most ESR integration studies are focused on a single control function. In contrast, recent work on renewable energy integration has employed the concept of enterprise control where the multiple layers of balancing operations have been integrated into a single model. This paper now uses such an enterprise control model to demonstrate the relative merits of load following reserves and energy storage integrated into the resource scheduling and balancing action layers. The results show that load following reserves and energy storage resources mitigate imbalances in fundamentally different ways. The latter becomes an increasingly effective balancing resource for high net-load variability and small day-ahead market time step.

I. Introduction

Traditionally, power system balancing operations consist of three consecutive control techniques, namely, security-constrained unit commitment (SCUC), security-constrained economic dispatch (SCED) and automatic generation control (AGC), where each consecutive control operates at a faster timescale [1]. The power system operator keeps the generation and consumption balance in the system by scheduling sufficient amounts of load following, ramping and regulation reserves. Each of these is applied to an individual control technique. However, these control activities are often coupled and therefore analyses restricted to a single control action do not give a complete picture of the evolution and development of power system imbalances [2]. Recently, power grid *enterprise control* modeling has been developed to holistically incorporate the multiple layers of balancing operations; thus capturing the control interactions at different timescales. The benefits of holistic power system modeling have been demonstrated in the integration of renewable energy, the determination of power system imbalances and the assessment of reserve requirements [3], [4].

Similar to power system reserves, energy storage resources (ESRs) can have various applications in power system operation and control, depending on their type and physical characteristics [5]–[8]. ESRs may be integrated 1.) as an energy resource in the unit commitment model [9]–[11], 2.) as a load following resource [12], 3.) and as a regulation resource [13] with the first two integration applications being considered within the scope of this paper. Integration into the unit commitment model accomplishes several goals simultaneously. Besides peak-load shaving and system operating cost reduction, the inclusion of additional constraints can also lead to emission and congestion reduction [9], [10]. The integration of an ESR as a load following resource reduces the actual load following requirements and hence the system cost. Two types of operation modes can be chosen: fixed pattern and load following [12]. When choosing the operating mode, there is a tradeoff between the risk of battery shortage/surplus and the quality of the imbalance mitigation.

Bo Jiang is with the Engineering Systems and Management Department at the Masdar Institute of Science and Technology, Abu Dhabi, UAE. amuzhikyan@masdar.ac.ae

Amro M. Farid is an Associate Professor of Engineering with the Thayer School of Engineering at Dartmouth, Hanover, NH, USA. He is also a Research Affiliate with the MIT Mechanical Engineering Department. amfarid@dartmouth.edu, amfarid@mit.edu

Kamal Youcef-Toumi is a Professor of Mechanical Engineering at the Massachusetts Institute of Technology, Cambridge, MA, USA. youcef@mit.edu

A review of the existing ESR literature shows that most studies are focused on a single time scale [6], [7]. This implicitly assumes that the impact of ESR integration into a given control technique is restricted to its associated timescale; thus neglecting potential interactions between timescales. As a result, the possible benefits of the ESR integration that lie outside the scope are missed. Similarly, the possible negative impacts on the adjacent timescales are also ignored. As part of its novelty, this paper studies the integration of energy storage resources into a power system enterprise control model [3], [4] for the first time. Such a methodology allows for a detailed understanding of how the energy storage resources interact with the rest of the power system enterprise control and its resultant imbalances.

The purpose of this paper is to demonstrate the differences in imbalance mitigation performance of energy storage resources and load following reserves. While these two resources are often discussed interchangeably, the enterprise control simulation experiments at the end of the work emphasize their differences and relative merits. These simulations demonstrate each resource's relative efficacy with respect greater variability in the net load and changes in the day ahead market time step. One main advantage of energy storage resources is the flexibility with which they may be scheduled. This paper chooses to use a novel scheduling approach previously described elsewhere [14]. Although this work has direct implications on the sizing and pricing of ESRs, these specific issues are excluded from the scope of this discussion.

This paper is organized as follows. Section II introduces the concept of power system enterprise control [3], [4]. Section III then describes the customizations made to the enterprise control in order to integrate ESRs. Section IV discusses the imbalance mitigation role of energy storage in contrast to load following reserves. Section V then presents the simulation results with respect to two key temporally dependent parameters: net load variability and day ahead market time step. The paper is brought to a conclusion in Section VI.

II. Background

This paper is concerned with power system balancing operations. As such, it adopts and customizes a three-layer enterprise control [3], [4] on top of the physical power grid as presented in Fig. 1. This section describes the enterprise control elements found in previous work while Section III describes the customizations made to integrate energy storage resources.

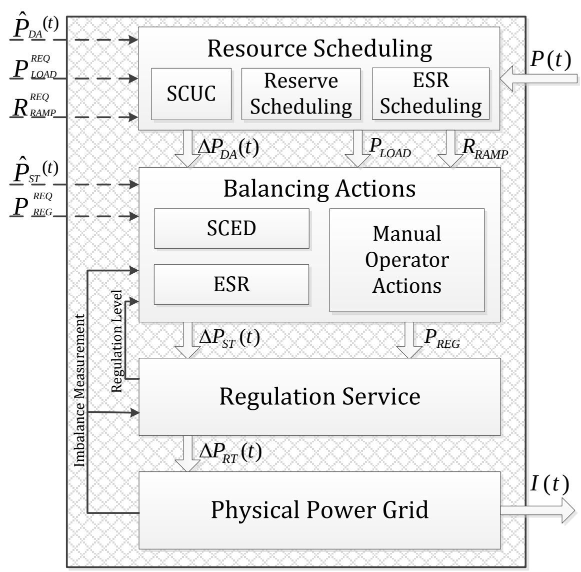

Fig. 1. Power grid enterprise control model w/ integrated ESR

Balancing operations are described by three consecutive stages, namely resource scheduling, balancing actions and regulation service. This classification replicates the hierarchy of controls: primary, secondary and tertiary [1], [15]. Each consecutive stage operates at a smaller timescale, that allows successive improvements of the power balance.

At the first stage, the security-constrained unit commitment (SCUC) determines the set of generation units that meet the real-time demand with minimum cost. In the original formulation, the SCUC problem is a nonlinear optimization problem [16]. However, a linearized formulation is often used to avoid convergence issues. Also, the SCUC uses the day-ahead net load forecast $\hat{P}_{DA}$ to determine generation. Since the forecast is not perfect, imbalances remain at the SCUC output:

$$\Delta P_{DA}(t) = P(t) - \hat{P}_{DA}(t) \tag{1}$$

At the resource scheduling stage, power system operators also schedule load following reserves to mitigate the imbalance (1) in the next stage [17]:

$$P_{res} = \beta_{DA}\sigma_{DA} \tag{2}$$

where σ_{DA} is the assumed standard deviation of (1) imbalance and β_{DA} is the confidence interval multiplier.

At the second stage, the security-constrained economic dispatch (SCED) uses the scheduled load following reserves to re-dispatch the generation based on the real-time state of the system. Originally, generation dispatch is a non-linear optimization model, called AC optimal power flow (ACOPF) [18]. The SCED is a commonly used linear optimization model [19], [20]. The short-term forecast $\hat{P}_{ST}(t)$ is used as an input which results in the following imbalance at the SCED output:

$$\Delta P_{ST}(t) = P(t) - \hat{P}_{ST}(t) \tag{3}$$

At the third stage, the regulation service uses the scheduled regulation reserves to mitigate the imbalances. The regulation service is generally represented by a dynamic model in combination with generator, prime mover and governor dynamic models [21]. The regulation requirement determination is similar to one of the load following reserves:

$$P_{reg} = \beta_{ST}\sigma_{ST} \tag{4}$$

where σ_{ST} is the standard deviation of the imbalance (3) and β_{ST} is the confidence interval multiplier. If appropriate amounts of each reserve is scheduled, the remaining imbalance $I(t)$ is within the acceptable range defined by NERC [22].

The reserve requirements (2) and (4) depend on a large set of power system and net load parameters classified into groups in Fig. 2. A more detailed discussion on relevance of each parameter to this study is presented in the methodology section.

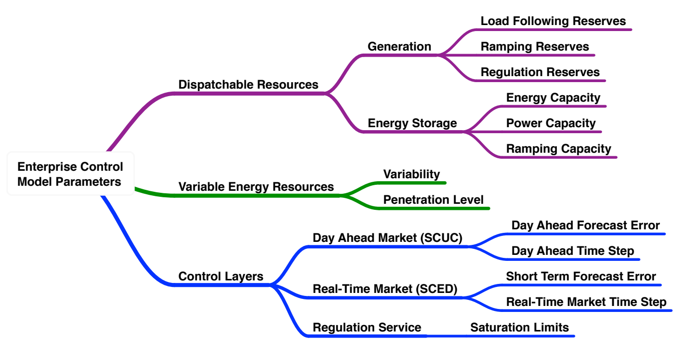

Fig. 2. Taxonomy of enterprise control parameters related to imbalance mitigation

III. Methodology

This section describes the enterprise control modifications required to integrate energy storage resources and their control. ESRs are integrated into the resource scheduling layer in two steps; first directly into the SCUC optimization program in Section III-A followed by post-processing step in Section III-B. The ESRs are also integrated into the balancing action layer in Section III-C.

A. ESR Integration into SCUC

This study uses the following formulation of SCUC with integrated ESR:

$$\min \quad \sum_{t=1}^{24}\sum_{i=1}^{N_G}(w_{it}C_i^F + C_i^L P_{it} + C_i^Q P_{it}^2 + C_i^U w_{it}^u + C_i^D w_{it}^d) \quad (5)$$

$$\text{s.t.} \quad \sum_{i=1}^{N_G} P_{it} + S_t = \hat{D}_t \quad (6)$$

$$X_t = X_{t-1} - \frac{S_t T_h}{d} \quad (7)$$

$$X_0 = X_{24} \quad (8)$$

$$w_{it}P_i^{min} \leq P_{it} \leq w_{it}P_i^{max} \quad (9)$$

$$R_i^{min}T_h \leq P_{it} - P_{i,t-1} \leq R_i^{max}T_h \quad (10)$$

$$S^{min} \leq S_t \leq S^{max} \quad (11)$$

$$X^{min} \leq X_t d \leq X^{max} \quad (12)$$

$$w_{it} = w_{i,t-1} + w_{it}^u - w_{it}^d \quad (13)$$

$$\sum_{i=1}^{N_G} w_{it}P_i^{max} - \sum_{i=1}^{N_G} P_{it} \geq P_{res} \quad (14)$$

$$\sum_{i=1}^{N_G} P_{it} - \sum_{i=1}^{N_G} w_{it}P_i^{min} \geq P_{res} \quad (15)$$

where the following notations are used:

C_i^F, C_i^L, C_i^Q	fixed, linear and quadratic costs of generator i
C_i^U, C_i^D	startup and shutdown costs of generator i
P_{it}	power output of generator i at time t
$\hat{D}_t$	total net load forecast at time t

P_i^{max}, P_i^{min}	max/min power limits of generator i
R_i^{max}, R_i^{min}	max/min ramping rate of generator i
T_h	scheduling time step, normally, 1 hour
N_G	number of generators
w_{it}	ON/OFF state of the generator i at time t
w_{it}^u, w_{it}^d	startup/shutdown indicators of generator i at time t
P_{res}	load following reserve requirement
S_t	ESR power output/input at time t
X_t	ESR state-of-charge (SOC) at time t
S^{min}, S^{max}	ESR power limits
X^{min}, X^{max}	ESR state of charge limits
d	ESR size in MWh

The goal of the SCUC optimization program in (5)–(15) is to determine the generation and ESR schedules that meet the net load forecast $\hat{D}_t$ with minimum operation cost. Note that the net load forecast consists of the forecasted quantities of load and variable energy resources. The operation cost is reflected in the objective function (5) and consists of the generation cost and the generator startup/shutdown costs. As is commonly done in several renewable energy integration studies [3], [4], [23], the cost of VER generation is excluded from the objective function. The power balance equation (6) makes sure that the scheduled total generation P_{it} and the ESR supplied power S_t together meet the demand forecast $\hat{D}_t$.

In addition, the SCUC program is subject to a set of constraints associated with the physical characteristics of generation and ESR units. For the given ESR power output S_t, the energy drained during T_h time interval is S_tT_h. Accordingly, (7) states that the SOC change for each T_h interval should be equal to the drained energy normalized by the ESR capacity d. Note here, that the SOC X_t, has units of MWhr and neither assumes a given storage technology not assumes the energy domain in which the energy is stored (e.g. hydraulic, chemical, mechanical, etc). Also, (8) makes sure that the ESR returns to its initial state at the end of the operation day. Constraints (9) and (10) set the generation power and ramping limits respectively. Similarly, constraints (11) and (12) set the ESR capacity and power limits respectively.

Besides defining the generation and ESR schedules, the SCUC program also schedules additional generation capacity called load following reserves to compensate for possible forecast errors and net load variability. The scheduling of upward and downward load following reserves are reflected in (14) and (15) respectively. Finally, the constraint (13) sets up a logical relationship between the generation startup/shutdown events and their ON/OFF states.

It is important to notice, that the objective function (6) only contains the generation cost from the thermal power plants and neglects the costs associated with the ESR, load following reserves and variable energy resource (VER) generation. As a matter of fact, inclusion of these costs allows the optimization program to decide which technologies are economically more feasible to use and find the optimal tradeoff between competing technologies.

However, the goal of this paper is to study the merits of each technology in terms of imbalance mitigation performance. To achieve this goal, it is absolutely crucial to have control over the amounts of each type of technology available in the system and not to leave this decision to the optimization program. To this end, this study assumes that the amounts of the load following reserves, the ESR and the VER penetration level are given in advance and are independent of the costs associated with them. As a result, these costs are excluded from the objective function. Future SCUC market designs may then use the "baseline" cost-independent results from this work when implementing the cost roles of not just ESRs but also ancillary services in general.

B. SCUC-Post Process for Integrated ESR Scheduling

The generation and ESR schedules provided by the SCUC problem have T_h (e.g. hourly) time resolution. As a result, on a finer timescale the generation schedule has a stair-like profile with constant values for each hourly interval. And yet, this stair-like profile does not capture the overall intra-period rising and falling trends of the demand. As a result, even in the absence of forecast error, the load following reserves must be deployed to meet the relatively smooth real-time demand profile [17]. This paper utilizes a previously developed method [14] to exploit the flexibility of ESRs as a post-process to the SCUC. It is recalled here for continuity.

As stated above, the SCUC provided ESR schedule has hourly resolution, while its profile within each hourly interval is undefined. This allows designing a sub-hourly ESR profile based on the SCUC output that, in addition to the traditional benefits of peak load shaving and operating cost reductions, also simultaneously reduces the load following reserves requirement. The newly designed ESR schedule is based on "piecewise linear harmonic" functions and resembles the smooth demand profile within hourly intervals better than the stair-like profile, thus, reducing the load following reserve requirement. However, to maintain the compatibility of the designed ESR schedule with the SCUC solution and maintain it within the ESR physical limits, the following three constraints are imposed on the desired ESR profile:

- **Constraint 1**: The new schedule and the SCUC result must have the same net energy exchanged within any given SCUC time period T_h.
- **Constraint 2**: The ESR can not exceed its energy storage limit at any moment.
- **Constraint 3**: The ESR can not exceed its power limit at any moment.

1) The Desired Schedule: While the integration of ESR into the SCUC problem reduces the total generation cost, its scheduling flexibility can also be used to reduce the load following requirements of the system. As already mentioned above, the stair-like profile of the generation schedule is one of the factors that affects the load following requirements. To this end, the desired ESR schedule should ideally make $generation + ESR$ schedule smooth:

$$Z(t) = P(t) + S(t) \tag{16}$$

The smooth profile $Z(t)$ is represented by the following expansion:

$$Z(t) = \sum_{n=-\infty}^{\infty} C_n \hat{f}_n(t) \tag{17}$$

where $\hat{f}_n(t)$ are "piecewise linear harmonic" functions derived from the Fourier series. Consider the the family harmonic functions $f_n(t)$

$$f_n(t) = e^{i\frac{2\pi nt}{N_h T_h}} \tag{18}$$

They may be sampled at the time step of the real-time market T_m to give:

$$f_{n\kappa} = f_n(\kappa T_m) \tag{19}$$

Piecewise linear functions are then defined around these point values.

$$\hat{f}_n(t) = f_{n\kappa} + \frac{t - \kappa T_m}{T_m} \left(f_{n,\kappa+1} - f_{n\kappa} \right), \kappa T_m \le t \le (\kappa + 1) T_m \tag{20}$$

where $\kappa = 0, 1, ..., N_m$. N_m is the number of T_m intervals in one day.

The number of C_n coefficients in (17) should be within the Nyquist limits to eliminate the potential for aliasing. While C_n are complex numbers and introduce $2n$ variables, half of these may be eliminated so as to match the total number of available SCUC outputs. The Fourier coefficients are pairwise complex conjugates and C_0 is pure real. Also, for the n corresponding to Nyquist frequency, the real part of $f_n(t)$ is a half period cosine in the T_h interval and its integration always returns zero. To avoid singularities, the corresponding coefficient is excluded.

In order to solve for the C_n coefficients and tie the ESR schedule to the SCUC, Constraint (6) described above must be observed. According to (7), the amount of exchanged energy during interval k is:

$$E_k = S_k T_h \tag{21}$$

To maintain the peak-shaving process and the economical benefits of the SCUC output, the amount of exchanged energy during each time interval should stay the same as in (21):

$$\int_{kT_h}^{(k+1)T_h} S(t)\mathrm{dt} = S_k T_h \tag{22}$$

Thus, integration of the left-hand-side of (17) becomes:

$$\bar{Z}_k = \frac{1}{T_h} \int_{kT_h}^{(k+1)T_h} \left(S(t) + P(t) \right) \mathrm{dt} = S_k + \frac{1}{T_h} \int_{kT_h}^{(k+1)T_h} P(t)\mathrm{dt} \tag{23}$$

and depends on the SCUC output for ESR and the generation schedule, which are known at this point. Integration of the right-hand-side of (17) yields the following:

$$\bar{Z}_k = \frac{1}{T_h} \int_{kT_h}^{(k+1)T_h} \left(\sum_{n=0}^{N_h-1} C_n \hat{f}_n(t) \right) \mathrm{dt} = \sum_{n=0}^{N_h-1} C_n \frac{1}{T_h} \int_{kT_h}^{(k+1)T_h} \hat{f}_n(t)\mathrm{dt} \tag{24}$$

Now consider the last term of (24) and define an $n \times n$ matrix $\hat{f}_{nk}$ as

$$\hat{f}_{nk} = \frac{1}{T_h} \int_{kT_h}^{(k+1)T_h} \hat{f}_n(t)\mathrm{dt} \tag{25}$$

Note that $\hat{f}_{nk}$ does not depend on the demand profile and the storage schedule and can be calculated in advance. Equation (24) then takes the following form:

$$Z_k = \sum_{n=0}^{N_h-1} C_n \hat{f}_{nk} \tag{26}$$

which may be represented as a system of linear equations with C_n unknowns. In matrix form:

$$Z = \hat{F}C \tag{27}$$

From the discussion above, $\hat{F}$ is a square matrix of full rank. Thus, C can be found from the inversion of $\hat{F}$ inversion:

$$C = \hat{F}^{-1}Z \tag{28}$$

After the C_n coefficients are found, the ESR schedule is constructed from (17) and (16):

$$S(t) = \sum_{n=-\infty}^{\infty} c_n \hat{f}_n(t) - P(t) \tag{29}$$

And the state-of-charge becomes:

$$X(t) = X_0 - \int_0^t S(\tau)\mathrm{d}\tau \tag{30}$$

2) Schedule Scaling: The designed schedule has yet to comply with the ESR power and energy limits (Constraints 2 & 3). To this end, a proper scaling of both power and energy profiles should be performed to ensure they are within these limits and, hence, the ESR is able to follow the designed schedule.

Both power and energy scaling are done with reference to S_k to maintain the relation in (22). For each T_h interval, a scaling parameter α is defined as a ratio of the distance from S_k to the ESR minimum/maximum limits and the maximum deviation of the designed profile from S_k. Each time interval yields scaling parameters for both energy (α_k^E) and power (α_k^P) schedules. However, since the energy and power are related by a linear integration/differentiation operators, scaling one of the profiles also scales the other one. Thus, scaling can be done only once by using the smaller parameter of the two:

$$\alpha_k = \min\left(\alpha_k^E, \alpha_k^P\right) \tag{31}$$

If $\alpha_k \geq 1$, the schedule is within physical limits and is left unchanged. Otherwise, a scaling is implemented as follows:

$$S_k^*(t) = S_k + \alpha_k\left(S_k(t) - S_k\right) \tag{32}$$

The corresponding SOC profile is found from (30).

a) Power limits: The ESR power schedule should be scaled within S^{min}, S^{max} limits. To this end, the scaling parameter for interval k is defined as:

$$\alpha_k^P = \min\left(\frac{S^{max} - S_k}{S_k^{max} - S_k}, \frac{S_k - S^{min}}{S_k - S_k^{min}}\right) \tag{33}$$

where S_k^{max}, S_k^{min} are the maximum and minimum values of $S(t)$ during interval k.

b) Energy limits: According to (30), a constant level S_k in the power domain corresponds to the linear ramp in the energy domain from $X(kT_h)$ to $X((k+1)T_h)$. Using $\bar{X}_k(t)$ notation for the corresponding linear ramp in time interval k, the scaling parameter is defined as:

$$\alpha_k^E(t) = \begin{cases} \frac{X^{max} - \bar{X}_k(t)}{X_k(t) - \bar{X}_k(t)} & \text{if } X_k(t) - \bar{X}_k(t) > 0 \\ \frac{X^{min} - \bar{X}_k(t)}{X_k(t) - \bar{X}_k(t)} & \text{if } X_k(t) - \bar{X}_k(t) < 0 \end{cases} \tag{34}$$

$$\alpha_k^E = \min\left(\alpha_k^E(t)\right) \tag{35}$$

In such a way, an ESR schedule that observes all three previously constraints has been constructed.

C. Balancing Layer Integrated ESR Scheduling

The energy storage resources are also integrated into the balancing timescale. In this case, a relatively simple version of the storage scheduling and control is implemented.

1) The Desired Schedule: The goal of the ESR at the balancing timescale is to mitigate the imbalances that occur due to the difference between the actual net load and the day-ahead scheduled generation and storage, described in the previous subsection. However, the net load profile is unknown in advance and its short-term forecast is used instead. Thus, to accommodate imbalances, the desired ESR $s(t)$ should have the following power profile:

$$s(t) = \hat{D}(t) - (P(t) + S(t)) \tag{36}$$

where $\hat{D}(t)$ is short-term forecast of the net load. The choice of the forecast horizon is a tradeoff between the ability to make a proper scheduling for a long period versus the increasing short-term forecast error as the forecast horizon increases. In the current study, a four hour forecast horizon with 5 minutes resolution is chosen. The forecast is updated synchronously with the SCED at every 5 minutes for increased accuracy. The state-of-charge profile $x(t)$ corresponding to (36) becomes:

$$x(t) = x(t_0) - \int_{t_0}^{t} s(\tau)\mathrm{d}\tau \tag{37}$$

where t_0 is the current time.

2) Schedule Scaling: The desired power and energy profiles $s(t)$ and $x(t)$ must be scaled so as to conform with their respective physical limits. As the balancing (middle) layer scheduling differs from resource scheduling (top) layer, the scaling process also differs.

First, β^P and β^E coefficients are introduced that indicate how much the desired profile violates the power and energy limits respectively. It should be noted that these coefficients are updated regularly at each real-time market time step i as more accurate forecast becomes available:

$$\beta_i^P = \max\left[\frac{s_i^{max}}{s^{max}}, \frac{s_i^{min}}{s^{min}}\right] \tag{38}$$

where s_i^{max}, s_i^{min} are the maximum and minimum values of the desired profile (36) during the forecast horizon. In contrast, the state-of-charge coefficient is defined in respect to the starting point $x(t_0)$:

$$\beta_i^E = \max\left[\frac{x_i^{max} - x(t_0)}{x^{max} - x(t_0)}, \frac{x_i^{min} - x(t_0)}{x^{min} - x(t_0)}\right] \tag{39}$$

Next, the scaling parameter α_i is calculated as follows:

$$\alpha_i = \min\left[\frac{1}{\beta_i^P}, \frac{1}{\beta_i^E}\right] \tag{40}$$

If $\alpha_i < 1$, the desired profile is scaled as follows:

$$s_i^*(t) = \alpha_i s_i(t) \tag{41}$$

IV. Imbalance Mitigation Role of ESR

This section discusses the imbalance mitigation role of energy storage resources from two perspectives: the frequency domain, and its "utilization efficiency".

A. Frequency Domain Interpretation of Energy Storage Resources

Although energy storage and load following reserves can often be used interchangeably for imbalance mitigation, there are key characteristics that distinguish them. These are best seen in the frequency domain. Consider (37). The power flow and state-of-charge profiles are related by an integration – a linear operation. Therefore, increasing the magnitude of the expected imbalance also increases the magnitude of the required stored energy proportionally. Therefore, the required energy storage depends on power dependent parameters such as the penetration level and forecast error in much the same way that the load following reserves do. However, the integration operation also involves a temporal component, which defines the specific differences between the performance of load following reserves and ESR.

A frequency domain representation can give a better insight into this subject. Consider the application of the Fourier transform and Parseval's theorem to (37). The root-mean-square magnitude of the storage state-of-charge per MW imbalance mitigated A_x becomes:

$$A_x = \frac{rms(x(t))}{rms(s(t))} = \sqrt{\frac{\int_{-\infty}^{\infty} \frac{1}{\omega^2} s(\omega)\mathrm{d}\omega}{\int_{-\infty}^{\infty} s(\omega)\mathrm{d}\omega}} \quad (42)$$

where $s(\omega)$ is the power spectrum of (36). The important message of (42) is that lower frequencies (slower changing components) have bigger contributions to the required energy storage. In contrast, the variability of the profile is dictated by the higher frequencies [17]. Thus, ESR are better suited for mitigation of imbalances in systems with high net load variability. This conclusion becomes more relevant, as VER integration increases the total variability of the net load [24]. The simulations in the next section numerically verify the correctness of this statement.

B. Utilization Efficiency of ESR

The "utilization efficiency" of some imbalance mitigation resources, such as load following reserves or energy storage, is defined in this paper as the amount of that resource required to mitigate $1MW$ of imbalance. For energy storage, this metric is measured in MWh/MW, while for load following reserve it is dimensionless MW/MW. Furthermore, when the "utilization efficiency" is multiplied price it provides a meaning of economic value of that resources relative to the quantity of imbalances that it mitigates.

Power system imbalances occur due to several reasons such as inaccurate net load forecast, limited resolution of the resources scheduling, net load variability. To this end, resources are scheduled for each timescale to mitigate imbalances. In the balancing layer, the imbalances are mitigated by either load following reserves, or energy storage, or both. The load following reserves required to mitigate a certain amount of imbalances are studied both analytically [17] and numerically [3], [4] in the existing literature. The main outcome of these studies is that the reserve requirement depends on the control layer and VER parameters presented in Fig. 2. By (2), the load following reserves are proportional to the standard deviation of the imbalances [17].

The purpose of the ESR scheduling technique presented in Section III-B is to provide a smoother $generation + ESR$ schedule that resembles the actual net-load profile. As a result, and in the absence of forecast error, the designed profile should be able to mitigate all imbalances except the small variations with higher frequencies than the SCUC time step. However, the inevitable presence of the forecast error creates an additional imbalance component. Since the forecast resolution matches with the SCUC time step, the forecast error component of imbalances consists of frequencies lower than the SCUC time step. Thus, the effective imbalance consists of two components: high frequency small component and low frequency component, whose magnitude depends on the forecast error.

According to the discussion in the previous subsection, the ESR is better utilized for imbalances with higher variability. The imbalance high frequency component is directly related to the variability of the net load, while the variability of the low frequency component is related to the forecast resolution, i.e. the SCUC time step. Thus, it is expected that the utilization efficiency of the ESR should depend on the variability of the net load and the SCUC time step. To this end, the impact of these two *temporal* parameters on the ESR utilization efficiency is studied in this paper.

V. Numerical Results

As mentioned previously, the purpose of this paper is to demonstrate the differences in imbalance mitigation performance of the load following reserves and the ESR. Consequently, the first set of simulations validate the advantages of the ESR scheduling method described in Section III-B. The second and third set of simulations distinguish the performances of the load following reserves and the ESR with respect to the temporal parameters mentioned in Fig. 2; namely the net load variability and the day-ahead market time step. In order to focus the discussion, the generation ramping reserves, storage ramping, storage and power capacity were set to non-constraining values.

The IEEE RTS-96 reliability test system is used as the physical grid [25]. It is composed of three nearly identical control areas, with a total of 73 buses, 99 generators and $8550MW$ of annual peak load. Wind and load data from the Bonneville Power Administration (BPA) repositories [26] are used for this case study.

A. Storage Scheduling Method Validation

The power system operations are simulated for two different scenarios: with and without ESR integrated into the SCUC problem. As expected, the ESR integration reduces the peak load which also reduces the total generation cost, since the storage allows the accumulation of energy during the off-peak hours and generation during peak hours. The ESR starts accumulating energy at the beginning of the day, when the price is also low and returns the energy to the system during peak hours. This allows reducing the total operation cost of the system by $\sim 10\%$. At the end of the operating day, the storage restores its SOC to its initial value.

In order to better understand the impact of ESR on load following reserve requirement, the generation and ESR schedules are compared to the actual demand for the systems with and without ESR integration. Fig. 3 shows that the generation schedule of the system without ESR has a stair-like form, while the total $generation + ESR$ schedule of the system with ESR integration has a much smoother form and more closely resembles the actual demand profile.

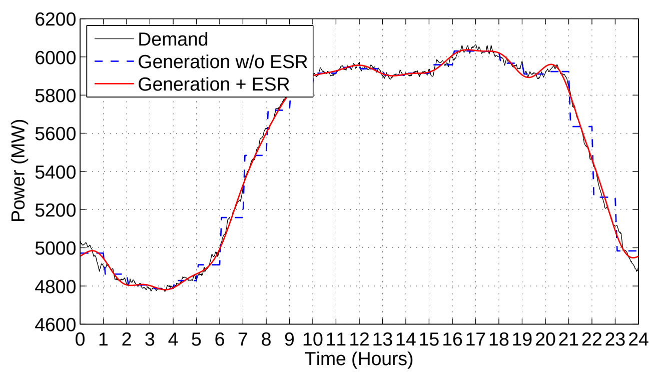

Fig. 3. The scheduled generation and storage for two scenarios

This difference defines the actual load following reserve requirement for each system. The load following reserve requirement for both cases are assessed as shown in Fig. 4. The load following reserve requirement corresponds to the point at which the imbalance curves go to zero; i.e. where additional reserves have no additional pose balancing effect. The results show that the load following reserve requirement of the system with ESR integration is significantly lower compared to the traditional system without ESR.

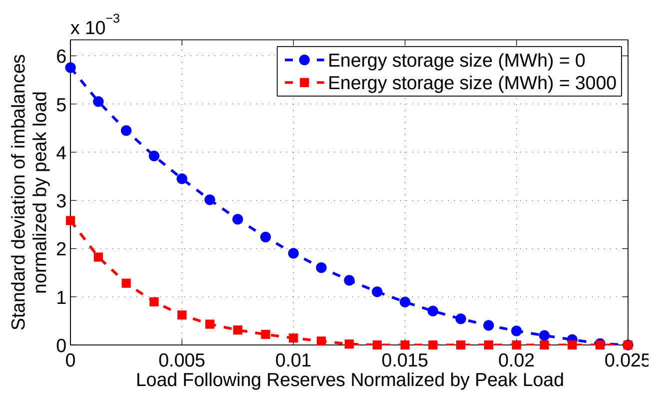

Fig. 4. The load following reserve requirements for different storage sizes

This case study shows that the different timescales of the power system are interconnected. Integration of ESR into the SCUC problem not only helps to shave the peak-load and reduce total operation costs, but it also reduces the load following reserve requirement of the system. This phenomenon would be impossible to observe if the study were limited to one time scale only. Thus, a holistic enterprise control approach to assess power system processes has been shown to address the interactions between different timescales.

B. The Impact of the Temporal Parameters

It is known that the load following reserve requirement is proportional to the standard deviation of imbalances [17], as shown in (2). In other words, the load following reserves have nearly fixed utilization efficiency measured as reserves per MW of imbalances. This section contrasts this phenomena for the ESR.

First, the impact of the net load variability on the ESR utilization efficiency is studied. Since the day-ahead forecast error normally has much higher magnitude compared to the high frequency component of imbalances, the forecast error is set to zero for this scenario to make the dependence on the net load variability more apparent. The results in Fig. 5 show that in the absence of the ESR, the standard deviation of imbalances is significantly higher for the system with higher net load variability. However, increasing the amount of ESR per MW of unmitigated imbalances reduces the imbalances faster for the system with higher variability. As a result, balancing the system requires less ESR per MW of unmitigated imbalances (the ESR has better utilization efficiency) in the case of higher variability. These results for the ESR contrast the findings for the load following reserves [3], [4]. It is important to mention that the magnitude of unmitigated imbalances is still higher in the case of higher variability. The difference is that the ESR is better suited for mitigation of the high variability imbalances.

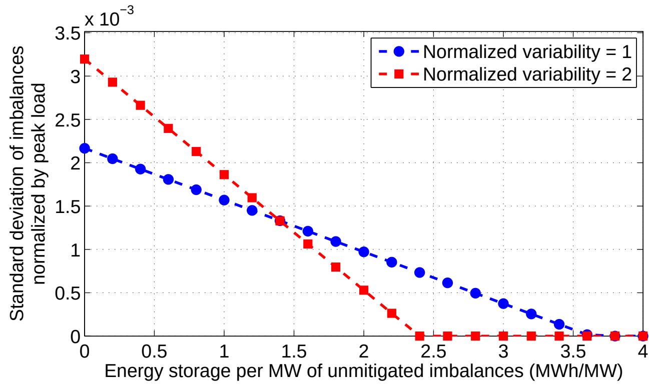

Fig. 5. The energy storage requirement per MW of unmitigated imbalances for different variabilities

A similar behavior can be observed for a power system equipped with both load following reserves and ESR, where the amount of ESR is fixed. The results in Fig. 6 show that the system with higher variability requires less load following reserves per MW of imbalances. This phenomenon is explained by the fact that the given amount of ESR is able to mitigate the imbalances more in the case of higher variability, hence, leaving less imbalances to the load following reserves. Thus, the ESR has better utilization efficiency for the systems with high net load variability.

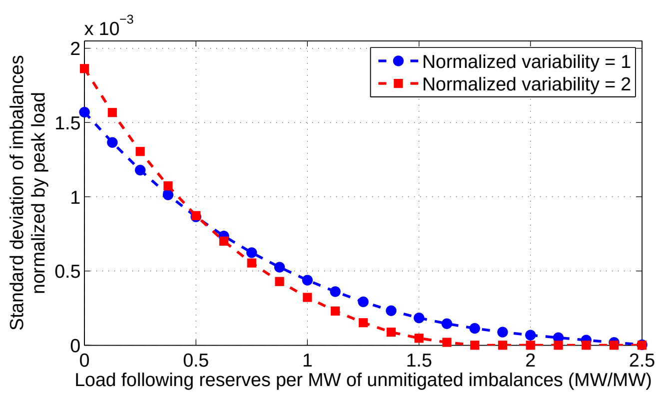

Fig. 6. The load following reserve requirement per MW of unmitigated imbalances for different variabilities

Next, the utilization efficiency of the ESR for different SCUC time steps is studied. As was discussed above, the SCUC time step defines the variability of the forecast error component of imbalances. Fig. 7 shows the utilization efficiency of the ESR for different values of SCUC time step. All graphs start at approximately the same point, which is mainly defined by the forecast error magnitude. The curve with smaller SCUC time step reaches the saturation sooner, hence, corresponds to better storage utilization efficiency. Similar to the previous case, this leaves less imbalances for the load following reserves to mitigate, which reduces their requirement as shown in Fig. 8.

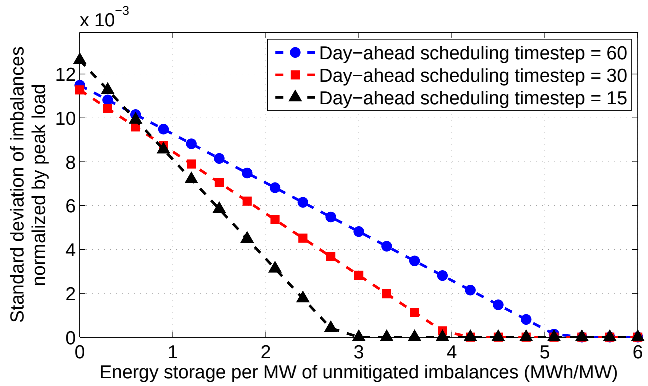

Fig. 7. The energy storage requirement per MW of unmitigated imbalances for different scheduling time steps

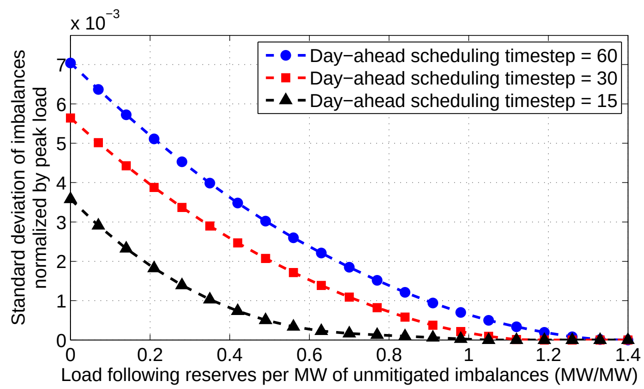

Fig. 8. The load following reserve requirement per MW of unmitigated imbalances for different scheduling time steps

VI. Conclusion

In conclusion, this paper has applied the concept of enterprise control to the integration of energy storage systems. While much of the existing ESR literature focuses on a single power grid balancing function, an enterprise control approach includes multiple layers of balancing operations within a single holistic model. As a result, the paper can demonstrate the relative merits of energy storage market integration and load following reserves. The paper has also developed a novel scheduling technique which beneficially exploits the coupling between the power system resource scheduling and balancing actions.

The results show that the ESR and the load following reserves have different performances and are better suited for applications in different circumstances. The utilization efficiency introduced here defines the amount of each type of resources the system needs per MW of unmitigated imbalances. While the utilization efficiency is nearly constant for the load following reserves, the performance of the ESR significantly depends on the temporal parameters, namely the net load variability and the day-ahead scheduling time step. Higher variability and smaller scheduling time step correspond to better utilization efficiency of the ESR.

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