Electrical Power and Energy Systems 74 (2016) 222–229

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Relative merits of load following reserves & energy storage market integration towards power system imbalances

Aramazd Muzhikyan [a,*], Amro M. Farid [b,c], Kamal Youcef-Toumi [c]

[a] Masdar Institute of Science and Technology, PO Box 54224, Abu Dhabi, United Arab Emirates
[b] Thayer School of Engineering Dartmouth College, 14 Engineering Drive, Hanover, NH 03755, USA
[c] Massachusetts Institute of Technology, Mechanical Engineering Department, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

ARTICLE INFO

Article history:
Received 31 July 2014
Received in revised form 29 May 2015
Accepted 9 July 2015
Available online 6 August 2015

Keywords:
Power system enterprise control
Energy storage resources
Power system operation
Renewable energy integration

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.

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.

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

* Corresponding author.
E-mail addresses: amuzhikyan@masdar.ac.ae (A. Muzhikyan), afarid@masdar.ac.ae (A.M. Farid), youcef@mit.edu (K. Youcef-Toumi).

http://dx.doi.org/10.1016/j.ijepes.2015.07.013
0142-0615/

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 'Background' introduces the concept of power system enterprise control [3,4]. Section 'Methodology' then describes the customizations made to the enterprise control in order to integrate ESRs. Section 'Imbalance mitigation role of ESR' discusses the imbalance mitigation role of energy storage in contrast to load following reserves. Section 'Numerical results' 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 'Conclusion'.

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 'Methodology' describes the customizations made to integrate energy storage resources.

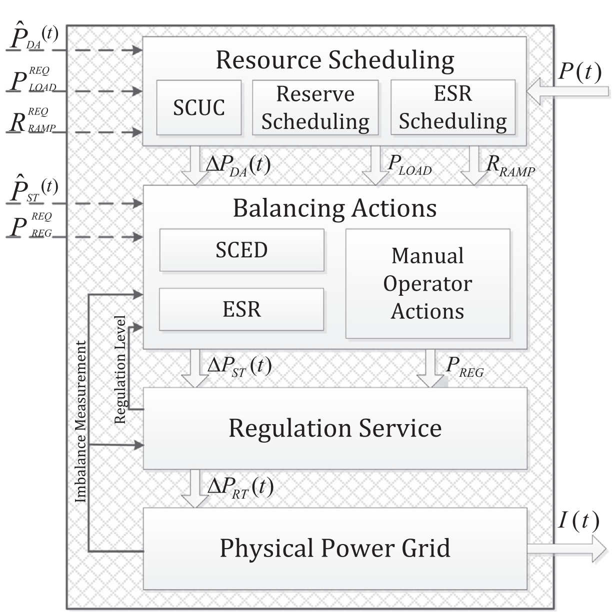

Fig. 1. Power grid enterprise control model w/integrated ESR.

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.

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 'ESR integration into SCUC' followed by post-processing step in Section 'SCUC-post process for integrated ESR scheduling'. The ESRs are also integrated into the balancing action layer in Sectio n 'Balancing layer integrated ESR scheduling'.

ESR integration into SCUC

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