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Energy Storage Systems in Emerging Electricity Markets: Frequency Regulation and Resiliency

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Abstract—**Different Federal Energy Regulator Commission (FERC) orders have provided the opportunity for battery energy storage systems (ESSs) to participate in markets. The ability to be a fast-ramping generator or load allows ESSs to provide different grid services. This paper discusses opportunities for ESSs to participate in multiple existing and future electricity markets. The economic value of ESSs can be further increased by pragmatically participating in markets and services considering operational and degradation aspects. The impact of ESS on grid resilience is discussed, including resilience-as-a-service. ESSs can restore the grid to its 100% resilient state during system events, and may also reduce the resilience degradation time during extreme events.**

Index Terms—**Battery energy storage systems, power system resilience, electricity markets.**

I. Introduction

Post deregulation, most bulk electricity services in the U.S. are organized through electricity markets to competitively provide electric resources for increased system reliability and economic efficiency. Synchronous generators, which have rotational inertia, traditionally dominated the bulk generation of power systems. Rising greenhouse gas (GHG) levels have encouraged investments in renewable energy sources (RES), the majority of which are intermittent in nature. In both the synchronous-generator-dominated grid, and the RES-dominated grid, there is a need for fast-ramping power sources to meet instantaneous changes in demand and supply [1].

Furthermore, recent advances in battery energy storage systems (ESSs), with new regulations and market frameworks, have facilitated the integration of ESSs in the U.S. bulk electric grid, represented in Fig. 1. ESSs can be used for various power system services, including regulation, load following, and energy shifting, leading to more economic and reliable grid operation. Due to the complexity in evaluating the economic profitability of ESSs, the definition of feasible business models, and the estimation of required incentives, the integration of ESSs has been an active research area. In addition to technical challenges, ESSs also face regulatory challenges. Organized markets in the U.S. operate under regulations enacted by the Federal Energy Regulatory Commission (FERC). Until recently, except pumped hydro, ESSs were not recognized as a bulk-power source by FERC. New regulations are required to integrate all ESS capabilities into the bulk-power system, and allow participation in every aspect of power system operations.

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State-of-the-art electricity market studies for storage in arbitrage and ancillary services in day-ahead, intra-day, and real-time markets argue that ESSs could be an economical and viable option if the owners have access to revenue from multiple markets through aggregation of benefits [2]. The participation of ESSs in frequency regulation and arbitrage can offer high revenue in electricity markets, especially in the future inverter-dominated grid with lower system inertia [1], [3], [4]. This paper discusses the emerging services, regulations, and markets available for ESSs and the future trends in this area.

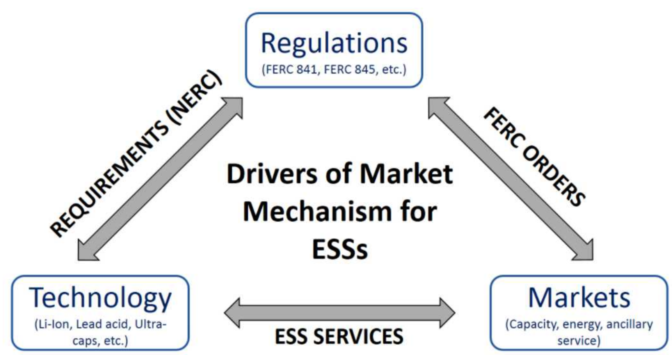

Fig. 1. Factors influencing ESS usage for various services in organized electricity markets.

II. Regulations Driving ESS Adoption

FERC is an independent agency responsible for transmission and wholesale sales of electricity in U.S. interstate commerce, including monitoring and investigating energy markets. Fig. 2 presents a visual representation of FERC orders that directly facilitate the deployment of ESSs.

Issued in 2007, FERC Order No. 890 was one of the first orders to facilitate ESS integration by allowing participation of non-generation technologies in deregulated markets. FERC issued Order No. 755 in 2011 to allow independent system operators (ISOs) to compensate ESS owners for the performance of services provided using non-generation technologies. PJM and CAISO were among the first ISOs to introduce the use of ESSs, primarily for frequency response. Combined, they deployed 78% of U.S. utility-scale ESSs as of 2016 (42% from

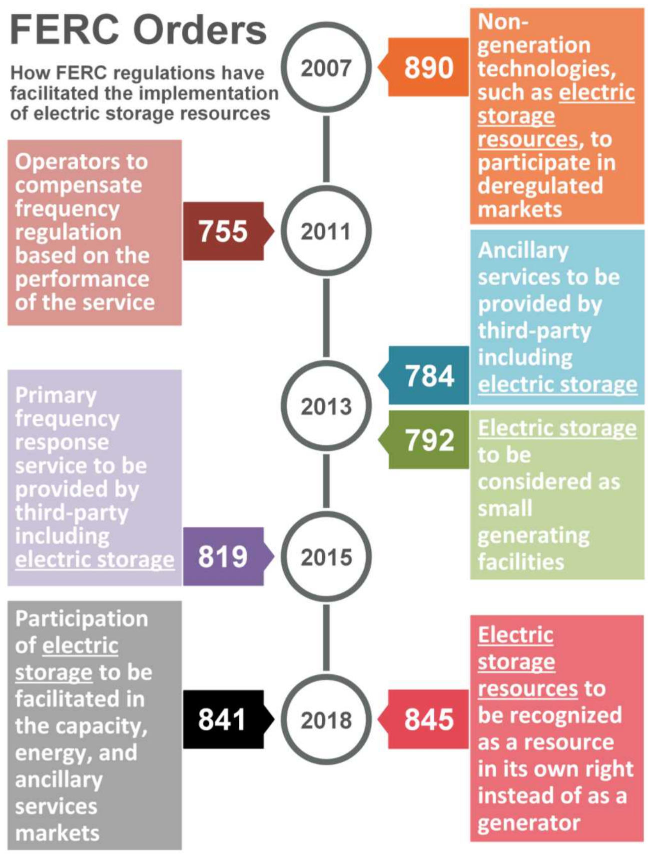

Fig. 2. Visual representation of the FERC orders that have facilitated the integration of electric storage resources.

PJM, 36% from CAISO) [5]. More recently, in Feb. 2018, FERC issued Order No. 841 to facilitate the participation of ESSs in the capacity, energy, and ancillary service markets. The order requires that ISOs revise their tariff and establish a participation model for ESSs, along with new market rules that consider their physical and operational characteristics (e.g., battery degradation) so they are properly compensated.

III. ESS Emerging Services

An important characteristic of ESSs is the ability of ESSs to inject and absorb power to behave as energy suppliers and consumers. Some of the potential benefits of ESSs are related to firming variable RES, and shifting RES from low demand periods to high demand periods [6]. ESS flexiblity allows participation in arbitrage, peak shaving, demand response, and voltage regulation.

In energy markets, ESSs can be used for *arbitrage* to buy and store energy when the prices are low, and sell the energy back when prices are high. The profit of this service depends directly on market prices and ESS performance. In this context, optimization based on historical market data, efficiency, losses, capital costs, and degradation should be considered to avoid overestimating potential revenue from ESS arbitrage [7], [8].

Traditionally, to avoid extra demand charges and reduce electricity bills, industrial customers use diesel generators and gas turbines to generate power during peak periods to perform *peak shaving*. Unlike traditional generators with fuel costs, ESSs can provide power during peak hours and charge during low demand periods. For utilities, ESSs can also reduce operational costs of generating power during peak periods, reducing the need for peaking units and temporarily deferring costly infrastructure upgrades.

In distribution systems with high percentage of RES, ESSs can be used to support *voltage regulation* and reduce RES curtailment [9]. Dynamic Volt/var control can coordinated through ESS power inverters, on-load tap changers (OLTCs), and other voltage control devices. ESSs have also emerged as candidates for *frequency regulation*, and *grid resiliency*.

A. Balancing and Frequency Control

The conventional frequency regulation process is divided into three stages (primary, secondary, and tertiary) with different time scales, shown in Fig. 3 [3]. The primary stage considers the inertial and governor response of generators, secondary stage the automatic generation control signal exchanged between balancing authorities, and tertiary the reserve deployment to avoid future events. PJM is one of the first interconnections to consider ESS services for frequency regulation, modifying the area control error (ACE) signal to differentiate traditional generators from fast-ramping units (e.g., ESSs) to properly reward the service according to FERC Order No. 755. This approach is explained in greater detail in Section IV-A.

ESSs can also support the inertial response of the grid. RESs are often interfaced to the grid through inverters, not providing inertial response. As the deployment of RES increases, there is a decline in mechanical system inertia, leading to larger frequency variations or even instability. RES variability may also keep ISOs from outputting the necessary power to stabilize system frequency during generation-load imbalances [10].

Even though a future low-inertia grid is likely, the conventional frequency regulation process has not been changed to allow new market mechanisms for inertial services [1], [3]. ESSs can make use of their fast-ramping characteristic, inverters, and control algorithms to mimic the inertia of a conventional system and provide *virtual inertia* (VI), as illustrated by Fig. 3.

B. Grid Resilience

Natural hazards and extreme weather conditions, equipment and network failures, and cyber/physical attacks negatively impact grid resilience. Resilience strategies in such situations must also consider options to improve grid flexibility and control. ESSs can act as an effective power source for improved resiliency through proper power system network placement and deployment, resilience-oriented optimal scheduling, and resilience market design.

One of the complementary value propositions of ESSs being an integral part of modern power systems is to improve the resilience with local supply of loads and RES curtailment reduction. From the perspective of the ESS energy management system (EMS), maintaining a minimum storage

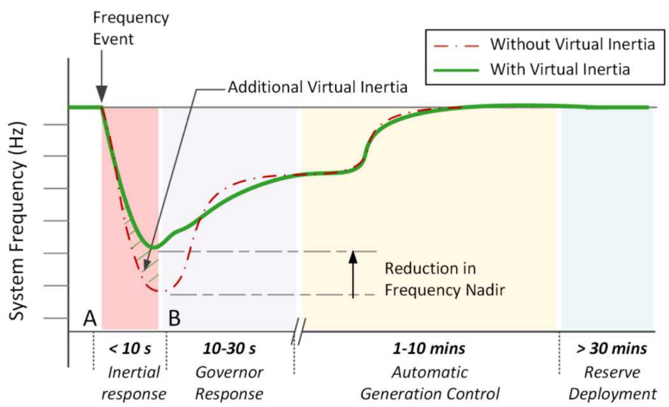

Fig. 3. Comparison of frequency response between a system with low inertia and a system with additional virtual inertia.

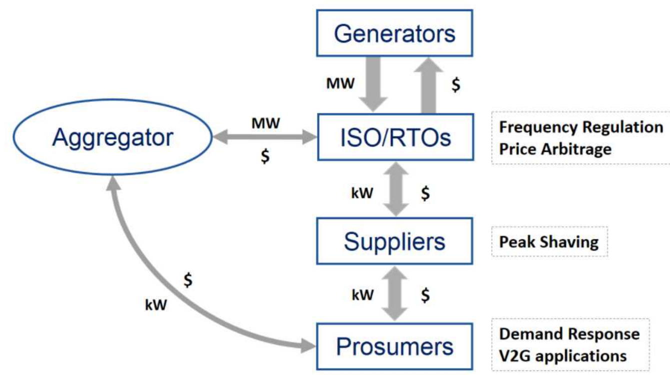

Fig. 4. ESSs participating in the bulk-power market through an aggregator. Other ESS services for different electricity market entities are also shown [9].

capacity constraint to supply essential loads during system events facilitates ESS resilience-as-a-service [9]. A resilience analysis framework of an electricity distribution system can further be investigated by mapping the derived ESS resilience attributes to corresponding economic factors to develop a grid-level resilience market [11].

IV. Considerations for ESS Participation in Electricity Markets

The integration of ESSs in electricity markets requires consideration of different aspects. With the reduction in cost of RES and ESSs, power system consumers have the capability to produce electricity and sell the excess to the electric supplier as *prosumers*, earning revenue from net metering or feed-in tariffs. Another approach for prosumers is to participate in the bulk-power market as a group of assets. Bulk-level ESSs can participate individually, or groups of smaller ESSs can participate through an aggregator, as shown in Fig. 4.

The aggregator provide services to each market entity by coordinating and optimally dispatching a large number of prosumer assets based on their capabilities, maximizing their revenue in the appropriate market(s). Beyond optimizing distributed ESSs owned by prosumers, aggregators can better integrate RES to the wholesale market. One example is presented in [12], where the interaction between the wholesale market and a prosumer aggregator with PV and ESSs decreases the prosumer operating costs by avoiding distribution costs.

A. ESS Ancillary Service Markets Challenges/Opportunities

Services that are provided by entities to support power quality and reliability of the bulk electric power system from generation to distribution are known as ancillary services. The two main ancillary services provided are *regulation* and *reserve*. *Regulation* makes up for the small mismatches between generation and demand, while *reserves* make up for the loss of generation or large increase in demand. The most important feature required for generating entities participating in ancillary service markets is the ramp capability for changing the power output. Inverter-based ESSs are one of the fastest resources to provide regulation services, increasing their value.

Given the variety of services ESSs can provide, and the potential benefits of stacking these services, several case studies have been conducted to evaluate the value proposition of ESSs. The potential revenue for the Sterling Municipal Light Department ESS was estimated considering participation in arbitrage, frequency regulation, and grid resilience by optimizing the value streams to maximize the benefit of energy storage [13]. The study suggests that co-optimization of all ESS value streams, along with better monthly peak prediction, could reduce the need of additional ESS capacity.

Other studies looked at the value proposition from the U.S. markets perspective (ERCOT [14], [15], CAISO [7], PJM [16], [17], and MISO [10]). Often, the main revenue potential for ESSs is related to frequency regulation and energy arbitrage, and participation in multiple energy market streams, however the results are location dependent. When compared to arbitrage in the day-ahead market, frequency regulation using ESSs yields significantly greater revenue, as presented in a case study for an ESS of 20MW/MWh in MISO [10]. A similar study compared arbitrage and frequency regulation for the same period in PJM provided by a 20MW/5MWh ESS, which would yield more than 6 million dollars with almost 100% of this revenue from frequency regulation services. Although in CAISO, a 1MW/4MWh ESS participating in day-ahead and real-time energy markets for arbitrage can potentially receive almost three times more revenue than just participating in day-ahead market [7]. These studies show that maximization of ESS revenue is location dependent, and is achieved by offering multiple services and participating in different energy markets.

Another example of ESS integration in energy markets is PJM, where ESSs are being used for frequency regulation and are compensated differently from conventional generators [1]. As ESSs are fast-ramping resources, they can provide power very quickly during frequency events with better performance. PJM split ACE into two signals: (i) RegA for traditional generator regulation, and (ii) RegD for dynamic regulation resources, made for fast-ramping resources like ESSs. With the different signals, PJM categorizes frequency response resources based on their capability, and rewards ESS owners (RegD) according to their improved performance in providing these services [1]. However, this mechanism still needs to improve coordination and include other physical characteristic considerations of ESSs.

A final challenge for ESS owners is to generate appropriate bids considering the influence of high RES penetration on generating costs and storage profits [18]. Thus, investments in ESSs requires a good understanding of ancillary markets, as well as expected power imbalances to establish bid pricing strategies. Thus, to promote ESS participation in the power grid, new market mechanisms considering operational complexities, capabilities, and benefits need to be developed.

B. Assessment of ESS Market Participation Value

The complexity of ESSs, combined with limited experience integrating ESSs in electricity markets, emphasizes the need of data and tools to identify and prioritize profitable services and markets for investors. In addition, the design of algorithms to manage ESSs and increase their economic value is critical. Advanced EMSs aim to maximize daily profits by optimizing market participation in different electricity markets while meeting reserve requirements [19]. These EMSs employ linear programming models to maximum profit, and can be employed in different ESS technologies [20]. Most models focus on revenue maximization, while often neglecting the costs associated with battery degradation from battery cycling. ESS lifetime can be significantly reduced due to cycle and calendar life losses depending on the frequency and intensity of use. The profitability of ESS participation in electricity markets depends not only on the revenue from provided services, but also on the cost of battery degradation [21], [22].

To participate in electricity markets, entities that own ESSs must bid at their marginal cost, thus the incorporation of the aging process is required to estimate value and manage ESS utilization. Battery cycle aging has been modeled using piecewise linear cost functions that can be incorporated into electricity market dispatch programs [23]. To integrate the degradation aspects, the cost function typically considers the depth of discharge (DOD) as the main factor contributing towards ESS degradation. However, the accuracy of these models are dependent on many variables (e.g., temperature, DOD, cycling history), and are different for each battery technology.

Traditionally, these models are obtained from experimental data, and are not made easily available by ESS manufacturers. Table I describes the different operating factors of ESSs and the relative influence on degradation for the identified grid application. For *power* intense applications (e.g., VI) that cycle batteries at a higher frequency than other applications, the existing degradation models might not be applicable as battery degradation characterization is not typically performed under these conditions.

Other aspects that need to be considered for ESS planning relate to location optimization, capacity estimation, and efficient dispatch to economically provide energy and regulation services. To support strategic decisions in multiple electricity markets, decision-support tools are being developed, e.g., QuESt [24], a tool that uses ISO market data to estimate ESS revenue.

TABLE I
BATTERY USE IMPACTS FOR ELECTRICITY MARKET APPLICATIONS

Grid Application	Battery Capacity	Cycle Depth	Current Rate
Frequency Regulation	Low	Low	High
Arbitrage	High	High	Medium
Peak Shave	Medium	Medium	Low

C. Challenge of ESS Resilience Metrics

The combination of services discussed in Section III can increase the operational resilience of the grid. ESSs are capable of improving transient and steady-state grid stability, maintaining adequate power quality, and avoiding black-outs. Currently, there are no standard resilience metrics, which increases the challenge for measuring resiliency, and ESS impact on resiliency (as it may differ per metric). Location, size, and response time are critical factors that influence ESS performance, and will impact the cost to benefit ratio of providing resiliency services.

To systematically assess the value of resilience enhancements of power systems with respect to critical events, a conceptual trapezoid is proposed in [25]. The trapezoid, illustrated for ESSs in Fig. 5, demonstrates the phases of a power system disturbance. The trapezoid includes the time sequence of these phases, and required recovery actions, enabling a dynamic, multi-phase resilience assessment with respect to operation and infrastructure [26].

The improvement on power system resiliency with ESSs can be visualized by the dotted trapezoid in Fig. 5. In Phase I, the ESS reduces the impact of initial events, and restores the grid to 100% resilient state in time $t_{ar} - t_{be}$. In case of an extreme event, ESSs provide an opportunity to improve the operational flexibility, thereby reducing the the resilience degradation level to RL_{es}, instead of RL_{ps} without ESS resiliency services. In Phase II, while identifying the critical components for system recovery to a resilient state, an alternate local grid can be formed by RESs with ESSs. Finally, in Phase III, ESSs can support power system restoration.

Because ESSs can play a major role in reducing the time and impacts on each event phase, the total time to restore the system ($t_{bn} - t_e$) to the pre-event 100% resilient state can be significantly reduced. In addition, trapezoid area resilience metrics can be used to quantify the resilience [25], but a simplified framework to assess economic viability of ESSs to improve resilience still needs to be developed. For that, more case studies of systems with high penetration of ESSs and the impact on power quality and reliability is needed, as well as determining other factors that can influence the capability of ESSs to improve resiliency. One example is the impact of battery degradation on resiliency, as it reduces the capability of ESSs to effectively support the grid.

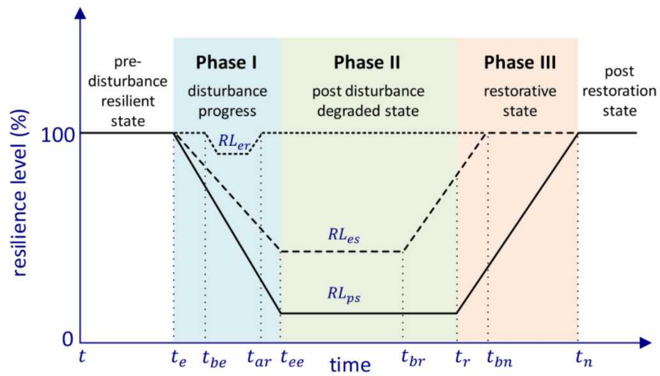

Fig. 5. ESSs impact on the power system resilience trapezoid.

V. Conclusions and Future Trends

This paper presented a review of current and future market opportunities for ESSs, and drivers within the technology, market, and regulation framework. FERC orders facilitate ESS participation in different electricity markets. With the increasing RES impacts on frequency regulation services (e.g., PV systems), ISOs must adopt new market mechanisms, or add novel complex features in existing frameworks, to solve the issues related to generator-based wholesale market structures. To maximize ESS revenue, battery degradation with respect to participation in stacked services must be evaluated in EMSs and economic analysis to ensure proper cost estimation of these services.

ESSs will have a major role in improving grid resilience, and there is a strong need of developing an electricity resiliency market. Operationally, because ESSs need to be ready for required grid services, adopting power system event prediction mechanisms in the market framework would help in preparing, scheduling, and economically dispatching ESSs in the market. Future ESS resiliency services may include RES curtailment minimization, black start support, and peaker replacement. It is possible that not all of these services are explicitly compensated in future markets, but they may influence underlying pricing mechanisms and regulations to foster ESS adoption in the bulk power system.

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