Battery Energy Storage Systems in Energy and Reserve Markets

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***Abstract*—Recent Federal Energy Regulatory Commission (FERC) Order 841 requires that Independent System Operators (ISOs) facilitate the participation of energy storage systems (ESSs) in energy, ancillary services, and capacity markets, by including ESS bidding parameters that represent the physical and operational characteristics. However, in the existing market frameworks that allow Battery Energy Storage Systems (BESSs) to participate, the bids and offers do not explicitly represent the physical and operational characteristics such as the state of charge (SOC), discharge rate, degradation, etc. This paper proposes a novel BESS operational cost model considering degradation cost, based on depth of discharge and discharge rate. The model is developed considering Lithium-ion batteries, and the approach can be applied to other conventional electrochemical batteries, but not flow batteries. A detailed bid/offer structure based on the proposed BESS operational cost functions is formulated. Thereafter, a new framework and mathematical model for BESS participation in an LMP based, co-optimized, energy and spinning reserve market, are developed. Three case studies are presented to investigate the impact of BESS participation on system operation and market settlement. The proposed model is validated on the IEEE Reliability Test System (RTS) to demonstrate its functionalities.**

***Index Terms*—Energy storage, electricity markets, locational marginal price, spinning reserve.**

NOMENCLATURE

A. Set and Indices

e	BESS, $e \in E$.
h	Blocks of customer bids, $h \in N_{CB}$.
i, q	Bus, $i \in I$.
j	Generators, $j \in J$.
k, t	Time (hour), $k \in K$.
n	Blocks of generator offers, $n \in N_{GB}$.
ES_i	Set of BESS connected to bus i.
G_i	Set of generators connected to bus i.

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Note: The parameters and variables are listed without their indices, for brevity.

B. Parameters

B	Element of susceptance matrix, p.u.
B^E_{Cap}	Battery energy capacity, MWh.
$C1$	Degradation cost based on depth of discharge (DOD) and discharge rate, \$/MWh.
a, b, c, d	Coefficients of $C1$.
C^B	Battery cost, \$.
C^{Ch}	BESS charging bid price, \$/MWh.
C^D	Customer's demand bid price, \$/MWh.
C^{ESR}	Spinning reserve offer price of BESS, \$/MWh.
C^G	Generator offer price for energy, \$/MWh.
C^{GSR}	Generator spinning reserve offer price, \$/MW.
C^{sd}, C^{su}	Shut-down/ start-up cost of generator, \$.
$DCR^{\max}$	Maximum discharge rate limit of BESS, p.u.
$DCR^{\min}$	Minimum discharge rate limit of BESS, p.u.
$\overline{P}, \underline{P}$	Maximum/minimum limit on power output of generator, MW.
$\overline{P}^{Ch}, \overline{P}^{Dch}$	Maximum charging/discharging limit of BESS, MW.
$\overline{P}^D, \overline{P}^G$	Demand bid/ Generator offer quantity, MW.
$\overline{P}^{GSR}$	Generator spinning reserve offer quantity, MW.
$\overline{SOC}$	Maximum state of charge (SOC) limit of BESS, p.u.
$\underline{SOC}$	Minimum SOC limit of BESS, p.u.
β^{Ch}, β^{Dch}	BESS charging/discharging capacity share, as a fraction of the available BESS energy capacity.
β^{SR}	BESS offer quantity share, for spinning reserve, as a fraction of available BESS energy capacity.
η	Battery round trip efficiency, %.

C. Variables

DCR	Discharge rate of the BESS, p.u.
E^{Ch}	Charging energy, MWh.
P^{ChE}, P^{DchE}	Charging/discharging power, MW.
P^{ESR}	Spinning reserve from BESS, MW.
P^D, P^G	Cleared demand/generation, MW.
P^{GSR}	Spinning reserve cleared from generator, MW.
P^{loss}	Power loss in the transmission line, MW.
SOC	State of charge, p.u.

SOC^{Dch}	SOC after the discharging operation, MWh.
SOC^{SR}	Energy capacity of the BESS cleared for spinning reserve provision, p.u.
SOC^{SRcap}	BESS cleared capacity for spinning reserve, MWh.
U, V	Binary variable $= 1$, if generator starts/shut downs, and 0 otherwise.
W^G, W^{SR}	Binary variable $= 1$, if energy/spinning reserve offer of generator is cleared, and 0 otherwise.
X	Binary variable $= 1$, if demand bid is cleared, and 0 otherwise.
$Z1, Z2$	Binary variable $= 1$, if BESS is charging/discharging, and 0 otherwise.
$Z3$	Binary variable $= 1$, if BESS is providing spinning reserve provision, and 0 otherwise.
δ	Voltage angle of the bus, radian.

I. Introduction

In RECENT years, there has been significant deployment of battery energy storage systems (BESSs) in the power system; for example, the total BESS capacity installed globally of 11 GWh in 2017 is expected to grow to 100-167 GWh by 2030 [1]. Grid scale BESSs, because of their operational flexibility, characterized by a fast response time, high ramp rate, and capability to provide upward and downward response, are competent resources to provide services in electricity markets.

Recent Federal Energy Regulatory Commission (FERC) Order 841 [2] requires that Independent System Operators (ISOs) facilitate the participation of energy storage systems (ESSs) in energy, ancillary services, and capacity markets, at par with other participants, by introducing changes in the market designs by December 2019. An important requirement regarding the ESS bidding parameters, noted in [2], is to account for their physical and operational characteristics such as the state of charge (SOC), discharge rate, etc.

As of now, the BESSs participate in different ways and market mechanisms across the ISOs [3]–[7]. The New York ISO (NYISO) was the first to initiate a market design in September 2018, whereby the ESSs could offer their services in the wholesale energy, capacity, and ancillary service markets, in line with the FERC Order [4]. In this market design, the physical and operational characteristics of an ESS, such as the upper/lower storage limits, SOC, response rate, etc., are taken into consideration.

In PJM, which has the highest installed BESS capacity of 300 MW in North America, BESS participates in the regulation market by submitting two-part offers (capability and performance); while in the energy market they can only submit positive MW offers (discharging offers) with a \$0 offer price [8], [9], [10]. However, the PJM market has been redesigned to comply with FERC Order 841 and BESS will be allowed to submit charging, discharging and continuous mode operation bids/offers based on cost curves to participate in the energy market; this change is expected to be operational by the end of 2019 [11].

In CAISO, the BESSs can participate in the day-ahead and real-time regulation markets by submitting simple price-quantity based bids and offers for these services [3], [5]. In ISO New England, under the ongoing market design changes, a BESS sized 5 MW or greater would be able to participate in the regulation market from December 2019 [6].

In Ontario, Canada, the Independent Electricity System Operator (IESO) procured 50 MW of ESS capacity in 2014 [7], which includes thermal energy storage, BESS, flywheels, and power-to-gas (hydrogen storage) technologies, which are deployed mainly for ancillary services provisions such as regulation, voltage control and reactive power support. However, the BESSs do not bid to provide these ancillary services but are procured and paid through long-term contracts. A review of the current practices adopted in various ISOs reveals the need for a unified market settlement framework, as required by FERC Order 841, which will allow BESSs to participate in various markets. to do so, they must submit bids/offers by capturing their physical and operational characteristics.

There is a growing body of literature on integrating ESSs into power system operations [12]–[15], some recent research has proposed integrating ESS into electricity markets [16]–[30]. While few works have focused on determining the optimal strategies for coordinated operation of a wind farm and the ESS facility owned by the same entity and participating in electricity markets [16]–[19], the participation of an ESS as a grid-scale, independently owned resource, in day-ahead and real-time markets is discussed in [20]–[30]. These works [20]–[30] consider optimal bidding and offering strategies, and dispatch models for ESS considering arbitrage, renewable energy sources (RES) integration, and ancillary service provisions.

In [20], an approach to simultaneously optimizing investments in new generation, and distributed and bulk storage technologies by minimizing the short-term operation cost is presented. In [21]–[25], the optimal bidding and scheduling of ESS in electricity markets from an owner's perspective, are presented. In [21], a bidding mechanism based on stochastic programming is developed for a group of ESSs that participate in the day-ahead market to provide energy and reserve capacity, and in the real-time market to provide energy. The uncertainty in market prices due to wind power fluctuations and the impact of ESS size and location are considered, to improve the bidding decisions made by the large ESS units. In [22], an optimal bidding strategy is proposed for a BESS, maximizing its benefits by participating in energy and reserve markets. In [23]–[25], optimal bidding and scheduling mechanisms for ESS using two stage optimization approaches are proposed. The first stage maximizes ESS profit, while the second stage maximizes the overall market benefit considering generation resources and ESS. However, the research in [20]–[25] neither considers the loss of life (degradation) aspects of an ESS, nor appropriately models the operational cost function of ESSs in terms of their physical and operational characteristics.

Battery degradation results in two types of aging: (i) calender aging, and (ii) cyclic aging. The capacity fading and increase in battery resistance over a period of time, without the influence of external factors, is referred to as degradation due to calender aging; the degradation that occurs due to the actual operation of the battery *i.e.*, its cycling during charging and discharging modes, is referred to as degradation due to cyclic aging and depends on the depth of discharge (DOD), discharge rate, the limits on the SOC, ambient temperature, etc. [31]. Degradation due to calender aging is minimal when short-term operation is considered, and hence can be neglected. Thus, a battery's degradation is directly influenced by its charging / discharging operations.

Few works have considered the battery degradation related to participation in electricity markets [26]–[30]. In [26], battery degradation is modeled by limiting the discharge cycle of the battery only, but the degradation aspect is not a part of the BESS operational cost function. While [27]–[30] have considered including battery degradation in modeling the BESS operational cost function. In [27], a BESS usage cost model was developed by considering degradation based on cycles and DOD, to determine the optimal schedules in the energy market. In [28], a piece-wise linear cost function based on battery cyclic aging, using the rain flow algorithm, was proposed, with bids designed based on the developed cost function. An optimal bidding strategy was proposed for a BESS in [29] considering the battery cycle life model and participation in day-ahead energy, spinning reserve, and regulation markets. In [30], an optimal control and bidding strategy for a BESS, considering the battery aging cost, to participate in performance based regulation markets, was proposed. However in these works [27]–[30], other important considerations such as the degradation due to discharge rates, have not been considered in the BESS operational cost function formulations.

Thus, BESS operational cost functions need to be modeled in proper detail, considering the important aspects such as degradation cost based on DOD and discharge rate, in a unified market framework, with the objective of maximizing the benefits of all participants. Furthermore, in the context of FERC Order 841, a generic market operations framework and mathematical model to integrate BESS into the electricity markets are urgently needed. The following aspects need be taken into consideration in developing the operating cost function of a BESS:

- When a BESS participates in the electricity market, its charging / discharging profiles are expected to be significantly different from those considered in its testing phase. Therefore, it is important to take into account the variable, and usage dependent, BESS degradation characteristics in the operational cost model.
- BESSs being limited energy sources, it is more realistic to formulate their operational cost functions and bids/offers in terms of their energy capacity or SOC, instead of power quantities.

Considering the above aspects, the main objectives and contributions of this paper are as follows:

- Develop a novel BESS operational cost function model considering the Degradation Cost, which is based on the DOD and discharge rate.
- Propose a bid/offer structure based on the functions, for BESS to participate in energy and spinning reserve markets, capturing the inter-relationships between the BESS charging bid and discharging offer quantities.
- Develop a generic market operations framework and comprehensive mathematical model for the integration of BESS in a locational marginal price (LMP) based, co-optimized, day-ahead energy and spinning reserve market including the detailed BESS operational cost function formulation, the charging bid and discharging offer structure, by properly representing the BESS physical and operational characteristics.
- The proposed operational cost functions and bid/offer structure correctly captures the actual cost of BESS operation, accounting for its degradation, thus providing realistic market clearing decisions. Investigate the impact of BESS integration on market dispatch, energy and spinning reserve prices, and other economic indicators, for various cases.
- All the above formulations and propositions appropriately meets the important requirement of FERC Order 841 to develop a participation model for ESSs, accounting for their physical and operational characteristics, such as the SOC, discharge rate, etc., in the ESS bidding parameters, so as to facilitate their participation in ISO markets.

The remainder of the paper is organized as follows: Section II presents the modeling of BESS operational cost function considering the Degradation Cost. Section III presents the BESS bid/offer structure and the framework of the proposed market, with BESSs. The mathematical model of the LMP-based BESS-integrated, co-optimized day-ahead energy, and spinning reserve market is presented in Section IV. The detailed results for different case studies are presented in Section V, and Section VI concludes the paper.

II. BESS Operational Cost Function Model

The special characteristics of a BESS enables it to participate in the electricity markets both as a load and a generator, and hence the BESS can submit bids to charge and offers to discharge. The bids and offers should reflect the marginal operating cost of the BESS. Furthermore, the BESS can also participate in reserve markets by providing its capacity, in the form of a discharge offer; the discharging quantity can be available during both charging and discharging operations.

It is to be noted that battery degradation is dependent on factors such as the DOD, discharge rate, limits on SOC, ambient temperature, etc., and these dependencies are nonlinear in nature. In order to reduce battery degradation modeling complexity, the following assumptions are made: (i) the impact of high temperature is disregarded as all BESSs have an appropriate climate control system; (ii) the impact of SOC limits is minimal, by appropriate choice of the minimum/maximum limits on SOC; (iii) assuming that the BESS charging and discharging energies are identical over a day's cycle, battery degradation only occurs during the discharge stage of the cycle, and the charging half cycle causes no cycle aging [28].

Thus, the operations cost of a BESS is comprised of the following components: (i) Degradation Cost Based on DOD and Discharge Rate, (ii) Spinning Reserve Cost.

A. *Degradation Cost Based on DOD and Discharge Rate*

In this work, we model battery degradation based on two important factors: DOD and discharge rate. When considering the BESS degradation due to DOD, an important factor to be considered is from what level of SOC the battery starts discharging and to what level it reaches at the end of the discharging interval. For example, let us consider two cases of battery discharge: (i) SOC of 100% to 40% (ii) SOC of 80% to 20%. Although the DOD in both cases is 60%, the degradation is more severe in case (ii), as per [32]. Hence it is very important to capture the impact of starting and ending levels of the SOC on the degradation cost. Furthermore, it is to be noted that it is a common practice to use the SOC as the state variable in BESS operation models rather than the DOD [21], [22].

In the context of ESS participating in the electricity markets, the ISOs typically adopt two modes: (i) ISO-monitored energy level mode, (ii) self-monitored energy level mode [4], [33]. In the former mode of participation, the SOC, and lower/ upper storage limits of the ESS are available to ISO, to ensure that the storages' schedules in the day-ahead and real-time markets are feasible within their operating limits. In the latter mode of participation, the ESSs themselves manage their energy level constraints, thus do not participate by providing their SOC level or other operating limits to the ISO. For example, in NYISO [4] both modes are available for the ESS to participate in the market, while in MISO [33], the ESSs participate only through ISO monitored energy level mode. In the proposed work, we consider that the SOC of the battery is known and monitored by the market operator, as practiced in NYISO.

The second important factor contributing the battery degradation are the high charging and discharging currents. In this work, the discharge rate of a battery, denoted by DCR, is expressed as the change of SOC per unit time, given as follows:

$$DCR_k = \frac{SOC_{k-1} - SOC_k}{T} = \Delta SOC_k \quad \forall k \in K \tag{1}$$

Since a 1-hour time interval is considered, $i.e., T = 1$.

In this work, discharge rate is represented in terms of 'C', where 1C denotes the full discharge of the battery in 1-hour, 2C the full discharge in 30 minutes, 3C the full discharge in 20 minutes and so on. In the same context, 0.5C denotes 50% of the full discharge in 1-hour.

In order to model the battery degradation correctly, it is important to understand the impact of DOD and discharge rate on the number of cycles. The relationship of DOD with battery cycle life for a Lithium-ion battery (at a given temperature and discharge rate) shown in Fig. 1, is obtained through tests and are provided by the battery manufacturer [34], [35].

The relationship between cycle life and DOD for the Lithium-ion battery as per the curve in Fig. 1 can be expressed as follows:

$$L(D) = \gamma D^{-\omega} \tag{2}$$

where, γ and ω, are coefficients capturing the relationship between the number of cycles and the DOD, for an assumed discharge rate of 1C, and their typical values are given in [34], [35].

Similarly, the relationship between cycle life loss and discharge rate for the Lithium-ion battery is shown in Fig. 2 [36]. It can be noted from Fig. 2, the impact of discharge rate on the cycle life is almost linear for discharge rates up to 3C and thereafter

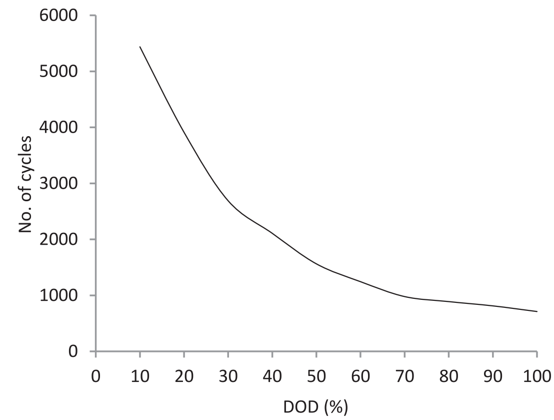

Fig. 1. Relationship between number of cycles and DOD, for discharge rate of 1C.

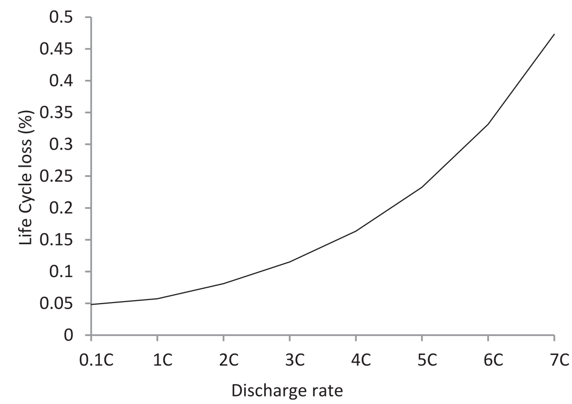

Fig. 2. Cycle life loss versus discharge rate.

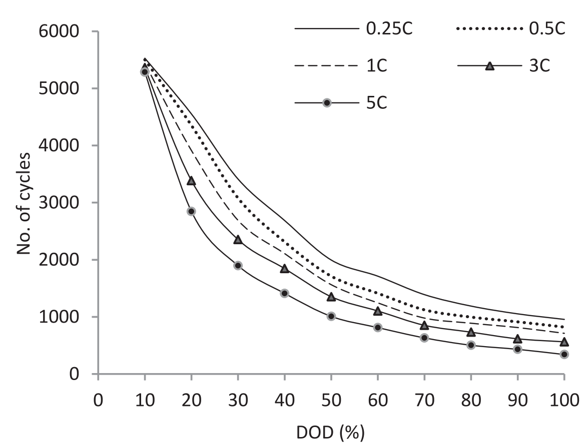

Fig. 3. Relationship between number of cycles and DOD, for different discharge rates.

it is exponential. With this inference, and the knowledge of parameters γ and ω for other values of discharge rates, the relationship between the number of cycles and DOD for various discharge rates can be developed, and represented as shown in Fig. 3.

Now, taking into account the impact of starting and ending levels of the SOC, before and after the discharge operation, the

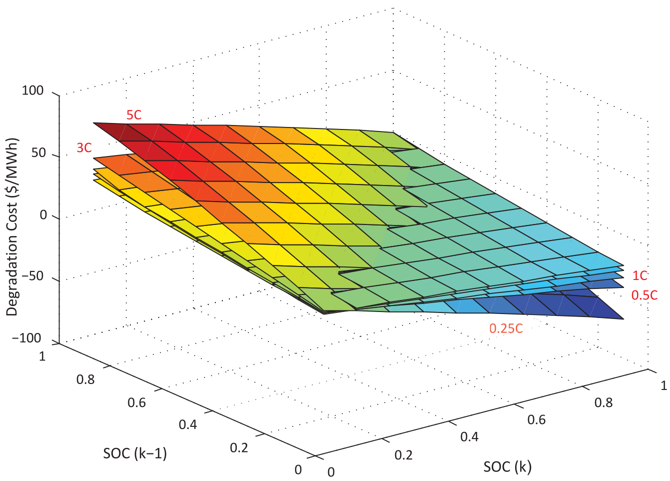

Fig. 4. Degradation Cost for various DOD and discharge rates.

Degradation Cost ($C1_k$) for a particular discharge rate, can be expressed in terms of the SOC as follows [32],

$$C1_k = \frac{C^B}{B^E_{cap}\eta^2\,\gamma}\left((1-SOC_k)^{\omega} - (1-SOC_{k-1})^{\omega}\right)\ \ \forall k \in K \tag{3}$$

Using (3), for different possible values of SOC_k and SOC_{k-1} and discharge rate, the battery degradation cost for various scenarios can be generated and represented as shown in Fig. 4; where each layer represents the Degradation Cost corresponding to various DOD, expressed in terms of SOC_k and SOC_{k-1}, and a particular discharge rate.

It is to be noted that $C1_k$ in (3) is a nonlinear function of DOD and discharge rate, expressed in terms of SOC_k and SOC_{k-1} and for different discharge rates. In order to obtain a operational cost function which can be easily integrated to a market model, the Degradation Cost function (3) can be linearized using the well known multi-linear regression method, and expressed as follows:

$$C1_k = aSOC_k + bSOC_{k-1} + cDCR_k + d \quad \forall k \in K \tag{4}$$

where, a, b, c and d are the coefficients of the Degradation Cost based on DOD and discharge rate.

It can be noted that the proposed Degradation Cost model of BESS is time dependent unlike the generator cost models, to account for the fact that the costs are based on DOD, SOC, and discharge rate, which are also time dependent.

In order to compare the accuracy of the linear regression model in (4) with a non-linear regression model, a non-linear regression analysis with the same data was carried out. It was noted that the 'Adjusted R-square' parameter, which measures the $goodness\ of\ fit$ of a multi-variable regression, was 0.8657 in linear regression and 0.9319 in nonlinear regression, which are very close. Furthermore, the corresponding 'Standard Error' values, which provide a measure of the variation of the estimated points from the actuals, were 5.17% and 3.79%, respectively, which are also close. Thus the linearized model used in (4) adequately represents the functional relationships between the Degradation Cost, DOD and the discharge rate.

B. Spinning Reserve Cost

The BESS can also participate in the spinning reserve market by providing its capacity, in the form of an offer. However, when the BESS provides spinning reserve, it forgoes the opportunity to participate in the energy-only market. Therefore, the opportunity cost of not participating in energy-only markets can be attributed to the spinning reserve cost of the BESS. The spinning reserve cost of the BESS is its opportunity cost, which is the difference in its revenue earnings from its participation in energy-only market with that in a co-optimized energy and spinning reserve market.

Assuming the BESS revenue in the co-optimized market is 75% of its earnings in energy-only market, its opportunity cost, and hence the spinning reserve cost, would be 25% of the revenue. Since the market price is unknown at the bidding stage, we assume that the spinning reserve cost is 25% of the BESS operations cost ($C1_k$). In the context of conventional generators providing spinning reserves, similar assumptions on the cost of spinning reserve have been made in [23], [37]. It is to be noted that the model simulation results will depend on the choice of the spinning reserve cost of the BESS. Actual data of bid/offer prices for energy or spinning reserve is nowhere available, as these are confidential. In the absence of such data, these assumptions become inevitable.

The BESS can offer spinning reserve when it is operating in discharging mode, charging mode or idle mode. While offering spinning reserve in the day-ahead market, the BESS would commit a reserve capacity. If this capacity is called or activated in real time, then in charging mode it would have to reduce that much capacity from its charging level and act as a demand response, while in, discharging mode it would have to additionally supply that reserve quantity, like a generation resource. And during its idle mode, the BESS can commit the capacity and provide reserve by either charging or discharging, if required. Furthermore, when required to deploy its reserve in real-time operation, the BESS will additionally receive the energy market price for the quantity of energy it supplied.

It is to be noted that flow batteries have a completely different degradation characteristic as compared to conventional electrochemical batteries (such as Lithium-ion, Lead-acid, Nickel-based, etc.,). In fact, it can be said that flow batteries have very low degradation [38]. Therefore, our proposed operational cost function model of the BESS is not applicable to flow batteries. In [35] battery characteristic curves and models for battery loss of life as a function of DOD, are presented for Lithium-ion and a few other conventional electrochemical batteries such as Lead-acid and Nickel metal halide. Since the Lead-acid and Nickel-based models in [35] are similar to Lithium-ion model, although varying in the mathematical function type, the proposed approach to model the operational cost of the Lithium-ion battery can be extended to these conventional electrochemical batteries. In this work, Lithium-ion batteries were considered because these are most widely used for grid-scale applications.

TABLE I
INTERPRETATION OF BESS BID/OFFER PARAMETERS

BESS Bid/Offer Parameters	Interpretation
a, b	Accounts for the impact of the DOD on the battery cycle life, which in turn affects the Degradation Cost.
c	Accounts for the impact of the discharge rate on the battery cycle, which in turn affects the Degradation Cost.
d	Linearization offset term in Degradation cost, depending on battery capacity.
$\beta^{Ch}, \beta^{Dch}, \beta^{SR}$	Denotes the fraction of the available battery capacity that is bid/offered for charging, discharging, and spinning reserve, respectively.

III. Proposed Structure of BESS Charging Bids and Discharging Offers

It is proposed that a grid-scale, independently owned BESS, will participate in the energy and spinning reserve markets in three ways (i) buy energy during charging operation, (ii) sell energy during discharging operation, and (iii) provide capacity in spinning reserve market during both charging or discharging operations. Accordingly, the BESS owner will submit bids to charge and offers to discharge, in the energy market, and offers to discharge and hence provide reserve capacity in the spinning reserve market. The structure of BESS bids/offers are discussed next.

A. Charging Bids

1) Charging Price: It is assumed that the BESS will seek to maximize the possibilities of energy arbitrage for making profit, hence it will submit a high charging bid price, such that it is cleared in the market during charging operation, to procure sufficient energy which it can discharge when the market price is high.

2) Charging Quantity: This is limited by a parameter $\beta^{Ch}_{e,k}$ denoting the fraction of BESS capacity available for charging. The BESS submits the $\beta^{Ch}_{e,k}$ parameter as its charging quantity bid in the energy market.

B. Discharging Offers

1) Discharging Price: The BESS owner submits offers to the energy market using $C1_k$ in terms of the coefficients a, b, c and d, as per (4).

2) Discharging Quantity: This is limited by a parameter $\beta^{Dch}_{e,k}$ denoting the fraction of BESS capacity available for discharging. The BESS submits the $\beta^{Dch}_{e,k}$ parameter as its discharging quantity offer in the energy market.

C. Spinning Reserve Offers

The BESS submits price-quantity offers to provide capacity in the spinning reserve market, during both charging and discharging operation, a price C^{ESR} and a parameter $\beta^{SR}_{e,k}$ denoting the fraction of the BESS capacity available for spinning reserve provision.

Table I presents a summary of all the BESS bid/offer parameters submitted by the BESS owners to the market operator, and their respective interpretations.

The ISO receives bids and offers from the various market participants. The loads submit the energy buy bids and the generators submit energy and spinning reserve offers. The structure of the demand bids and conventional generator offers are assumed to be as considered in [39]. The BESS submit the charging bids the discharging offers for providing energy and spinning reserve service, as per the structure discussed earlier. With these inputs, the energy and spinning reserve markets are simultaneously cleared using the novel and comprehensive joint optimization model, discussed in Section IV. The outcomes of the market settlement include the dispatch schedules, UC decisions, and market prices.

IV. Proposed Market Model Including BESS

A. Objective Function

Maximize the social welfare, given as follows:

$$
\begin{aligned}
J = & \underbrace{\sum_{k\in K}\left(\sum_{i\in I}\sum_{h\in N_{CB}}(C^{D}_{h,i,k}P^{D}_{h,i,k}) + \sum_{e\in E} C^{Ch}_{e,k}E^{Ch}_{e,k}\right)}_{\text{(a)}} \\
& - \underbrace{\sum_{k\in K}\sum_{j\in J}\left(C^{su}_{j,k}U_{j,k} + C^{sd}_{j,k}V_{j,k} + \sum_{n\in N_{GB}} C^{G}_{n,j,k}P^{G}_{n,j,k}\right)}_{\text{(b)}} \\
& - \underbrace{\sum_{k\in K}\sum_{j\in J}\sum_{n\in N_{GB}} C^{GSR}_{n,j,k}P^{GSR}_{n,j,k}}_{\text{(c)}} \\
& - \underbrace{\sum_{k\in K}\sum_{e\in E}\left(a_e SOC^{Dch}_{e,k} + b_e SOC^{Dch}_{e,k-1} + c_e DCR_{e,k} + d_e\right)}_{\text{(d)}} \\
& - \underbrace{\sum_{k\in K}\sum_{e\in E}\left(C^{ESR}_{e,k} SOC^{SRcap}_{e,k}\right)}_{\text{(e)}} \qquad (5)
\end{aligned}
$$

The gross surplus of customers and the BESS during charging, is represented in (a), the total cost of generators, which includes the generator start-up cost and shut-down cost, and the energy cost is represented in (b). The cost of spinning reserve provisions from generators is represented in (c), the cost of BESS for energy provisions during discharging, accounting for degradation based on DOD and discharge rate is given in (d). The cost of spinning reserve provision from the BESS during discharging, is represented in (e). The objective function in (5) is subjected to the following constraints,

B. Demand Supply Balance

This constraint is formulated using the dc load flow equations to ensure a balance between the supply and demand at each bus.

$$\sum_{j\in G_j} P^{G}_{j,k} + \sum_{e\in ES_i} P^{DchE}_{e,k} - P^{D}_{i,k} - \sum_{e\in ES_i} P^{ChE}_{e,k} = \sum_{q\in I}\left(0.5P^{loss}_{i,q} + B_{i,q}(\delta_{i,k}-\delta_{q,k})\right) \quad \forall i \in I, \quad \forall k \in K \tag{6}$$

The transmission line losses are included in the dc load flow equations using the approach discussed in [39].

C. Market Clearing Constraints

These constraints ensure that the cleared demand bids and generator energy and spinning reserve offers do not exceed their respective maximum bid and offer quantities.

$$P^{D}_{h,i,k} \le \overline{P}^{D}_{h,i,k}\, X_{h,i,k} \quad \forall i \in I, \forall k \in K, \quad \forall h \in N_{CB} \tag{7}$$

$$P^{G}_{n,j,k} \le \overline{P}^{G}_{n,j,k}\, W^{G}_{n,j,k} \quad \forall j \in J, \forall k \in K, \quad \forall n \in N_{GB} \tag{8}$$

$$P^{GSR}_{n,j,k} \le \overline{P}^{GSR}_{n,j,k}\, W^{SR}_{n,j,k} \quad \forall j \in J, \forall k \in K, \quad \forall n \in N_{GB} \tag{9}$$

D. BESS Energy Arbitrage Constraints

The following constraints ensure that the charging and discharging quantities cleared from a BESS are within its maximum bid and offer capacity.

$$SOC_{e,k} - SOC_{e,k-1} \le \beta^{Ch}_{e,k}\left(\overline{SOC}_{e} - SOC_{e,k-1}\right) + (1 - Z1_{e,k})\overline{SOC}_{e} \quad \forall e \in E, \quad \forall k \in K \tag{10}$$

$$SOC_{e,k-1} - SOC_{e,k} \le \beta^{Dch}_{e,k}(SOC_{e,k-1} - SOC^{SR}_{e,k-1} - \underline{SOC}_{e}) + (1 - Z2_{e,k})\overline{SOC}_{e} \quad \forall e \in E, \quad \forall k \in K \tag{11}$$

During the charging operation ($Z1_{e,k}$=1 and $Z2_{e,k}$=0), (10) becomes a binding constraint and (11) is a redundant constraint; thus (11) would be activated to ensure that the charging quantity cleared from a BESS is within its maximum bid capacity; and similarly, during discharging operation ($Z1_{e,k}$=0 and $Z2_{e,k}$=1), and vice-versa applies.

The SOC of a BESS at the end of the discharging operation need be within the limits and are ensured by the following constraints,

$$\underline{SOC}_{e}\, B^{E}_{Cap,e}\, Z2_{e,k} \le SOC^{Dch}_{e,k} \le \overline{SOC}_{e}\, B^{E}_{Cap,e}\, Z2_{e,k} \quad \forall e \in E, \quad \forall k \in K \tag{12}$$

where, the SOC after the discharging operation are obtained from the following,

$$SOC_{e,k}\, B^{E}_{Cap,e} - (1 - Z2_{e,k})\, \overline{SOC}_{e}\, B^{E}_{Cap,e} \le SOC^{Dch}_{e,k} \le SOC_{e,k}\, B^{E}_{Cap,e} - (1 - Z2_{e,k})\, \underline{SOC}_{e}\, B^{E}_{Cap,e} \quad \forall e \in E, \quad \forall k \in K \tag{13}$$

During the discharging operation ($Z2_{e,k}$=1), (13) determines the value of the SOC of the BESS at the end of the discharge interval and (12) ensures that the SOC is within its limits.

The cleared energy during charging operation is obtained as follows,

$$(SOC_{e,k} - SOC_{e,k-1})\, B^{E}_{Cap,e} - (1 - Z1_{e,k})\, \overline{SOC}_{e}\, B^{E}_{Cap,e} \le E^{Ch}_{e,k} \le (SOC_{e,k} - SOC_{e,k-1})\, B^{E}_{Cap,e} + (1 - Z1_{e,k})\, \underline{SOC}_{e}\, B^{E}_{Cap,e} \quad \forall e \in E, \quad \forall k \in K \tag{14}$$

$$\underline{SOC}_{e}\, B^{E}_{Cap,e}\, Z1_{e,k} \le E^{Ch}_{e,k} \le \overline{SOC}_{e}\, B^{E}_{Cap,e}\, Z1_{e,k} \quad \forall e \in E, \quad \forall k \in K \tag{15}$$

During the charging operation ($Z1_{e,k}$=1), (14) determines the value of the cleared energy of the BESS and (15) ensures that the cleared energy is within its limits.

The discharge rate of the battery is limited by its maximum/minimum discharge rate limits, given by,

$$DCR^{\min}_{e,k} Z2_{e,k} \le DCR_{e,k} \le DCR^{\max}_{e,k} Z2_{e,k} \quad \forall e \in E, \quad \forall k \in K \tag{16}$$

where the DCR is obtained from the following:

$$(SOC_{e,k-1} - SOC_{e,k}) - (1 - Z2_{e,k})\, DCR^{\max}_{e,k} \le DCR_{e,k} \le (SOC_{e,k-1} - SOC_{e,k}) + (1 - Z2_{e,k}) DCR^{\min}_{e,k} \quad \forall e \in E, \quad \forall k \in K \tag{17}$$

During the discharging operation ($Z2_{e,k}$=1), (17) determines the value of the discharge rate of the BESS and (16) ensures that the discharge rate is within its limits.

E. BESS Spinning Reserve Market Clearing Constraints

The cleared spinning reserve capacity from a BESS should not exceed its maximum offer quantity.

$$SOC^{SR}_{e,k} \le \beta^{SR}_{e,k}\, \overline{SOC}_{e}\, Z3_{e,k} \quad \forall e \in E, \quad \forall k \in K \tag{18}$$

The cleared spinning reserve capacity from a BESS is obtained from the following,

$$SOC^{SR}_{e,k}\, B^{E}_{Cap,e} - (1 - Z3_{e,k})\, \overline{SOC}_{e}\, B^{E}_{Cap,e} \le SOC^{SRcap}_{e,k} \le SOC^{SR}_{e,k}\, B^{E}_{Cap,e} - (1 - Z3_{e,k})\, \underline{SOC}_{e}\, B^{E}_{Cap,e} \quad \forall e \in E, \forall k \in K \tag{19}$$

If the BESS is cleared to provide spinning reserve ($Z3_{e,k}$=1), (19) determines the value of the cleared spinning reserve capacity from the BESS and (18) ensures that the cleared spinning reserve is within its limits.

F. BESS Operational Constraints

These include the energy balance, the limits on the SOC, charging/discharging power and the constraints to prevent simultaneous charging and discharging, as follows:

$$SOC_{e,k} = P_{e,k}^{ChE}\eta^{Ch} - P_{e,k}^{DchE}/\eta^{Dch} + SOC_{e,k-1} \quad \forall e \in E, \quad \forall k \in K \tag{20}$$

$$\underline{SOC}_e + SOC_{e,k}^{SR} \le SOC_{e,k} \le \overline{SOC}_e \quad \forall e \in E, \forall k \in K \tag{21}$$

$$0 \le P_{e,k}^{ChE} \le \overline{P}_e^{Ch} Z1_{e,k} \quad \forall e \in E, \forall k \in K, \tag{22}$$

$$0 \le P_{e,k}^{DchE} \le \overline{P}_e^{Dch} Z2_{e,k} \quad \forall e \in E, \forall k \in K \tag{23}$$

$$Z1_{e,k} + Z2_{e,k} \le 1 \quad \forall e \in E, \forall k \in K \tag{24}$$

G. System Spinning Reserve Constraints

These constraints ensure that the system spinning reserve requirement is met for each hour. It is assumed that the total system spinning reserve requirement is 10% of the gross demand at that hour,

$$\sum_j P_{j,k}^{GSR} + \sum_e P_{e,k}^{ESR} \ge 0.1 \left(\sum_i P_{i,k}^{D} + \sum_e P_{e,k}^{ChE} \right) \quad \forall k \in K \tag{25}$$

Where, $$P_{j,k}^{GSR} \le \overline{P}_j - P_{j,k}^{G} \quad \forall j \in J, \quad \forall k \in K \tag{26}$$

The cleared spinning reserve from a BESS is given as follows,

$$P_{e,k}^{ESR} = SOC_{e,k}^{SR}\, B_{Cap,e}^{E} \quad \forall e \in E, \quad \forall k \in K \tag{27}$$

H. Transmission Line Constraints

These constraints ensure that the line power flows are within their limits.

$$B_{i,q}(\delta_{i,k} - \delta_{q,k}) \le \overline{PFlow}_{i,q} \quad \forall i, \quad q \in I \tag{28}$$

I. Other Constraints

These constraints include generation limits, ramp-up/down constraints, minimum-up/down time constraints, coordination constraints, and line flow constraints, as discussed in [40] and not presented here for brevity.

V. Results and Discussions

To validate the proposed BESS integrated energy and spinning reserve market model, a slightly modified version of the IEEE RTS [41] is considered, which includes 32 generators, loads at 17 buses, and 37 transmission lines. There are 10 BESS units with total capacity of 250 MW/240 MWh spread over 5 buses as follows:

- Bus-4, 2 × [30 MW, 15 MWh]
- Bus-5, 2 × [30 MW, 30 MWh]
- Bus-9, 2 × [25 MW, 50 MWh]
- Bus-19, 2 × [20 MW, 12.5 MWh]
- Bus-20, 2 × [20 MW, 12.5 MWh]

TABLE II
All Day Aggregate Market Clearing Results

	Case 1	Case 2	Case 3
Energy cleared (MWh)	67,923	67,984	68,079
Generation dispatch (MWh)	68,928	69,059	69,121
BESS charging energy (MWh)	-	331	301
BESS discharging energy (MWh)	-	299	272
Losses (MWh)	1,005	1,043	1,013
BESS charging cost ($)	-	17,907	13,427
BESS degradation cost, C1 ($)	-	-	8,069
BESS spinning reserve cost ($)	-	7,582	7,831
BESS energy market revenue ($)	-	23,115	18,005
BESS spinning reserve market revenue ($)	-	15,979	16,143
BESS profit ($)	-	13,084	10,821
Social Welfare ($)	4,716,866	4,769,135	4,773,927

The loads at each bus are scaled up by 25% from the given data. The demand bids and generator offers for energy and spinning reserves are chosen as given in [39]. The BESS owners submit bids and offers for participating in the energy and spinning reserve markets, as discussed in Section III.

The proposed model is formulated as a mixed integer programming (MIP) problem and solved using the CPLEX solver [42] in GAMS [43]. To order to study the impact of BESS participation on market settlement and system operation, three case studies are considered as follows:

- Case 1: Base case without BESS participation.
- Case 2: BESS participation, simple bid/offer model.
- Case 3: BESS participation, proposed bid/offer model.

In Case 2 the BESS bids/offers do not take into account the degradation, and are solely based on market price forecasts. For the purpose of present studies, high charging bid prices and low discharging offer prices are considered. In Case 3, the values of the BESS bidding parameters are as follows: $a = -36.23$, $b = 34.80$, $c = 2.77$, $d = -2.45$, $\eta = 0.9$, $\beta^{Ch} = \beta^{Dch} = 0.5$ to 1, $\beta^{SR} = 0.1$ to 0.2, $\overline{DCR} = 1$, which are chosen based on the discussions in Section II, and [34]–[36].

Table II presents an aggregated summary of market clearing results. In Case 1, the cleared generators meet the cleared demand plus the system losses. In Case 2 & 3, there is a slight increase in the generation, which is to meet the additional BESS charging demand and the increased losses. However, as a result of BESS participation in the energy market, the cheaper BESS discharging offers could replace some of the expensive generators. Note that the charging/ discharging energy is more in Case 2 compared to Case 3. This is because, in Case 3 the Degradation Cost is accounted for, which limits the clearing of charging and discharging quantities from the BESS. It should also be noted that, when battery Degradation Cost is accounted for, it helps in the economic operation of the BESS and increases years of useful operation.

It is noted that the participation of BESS (Case 2 and Case 3) has resulted in an increase in the social welfare of the system, more so in Case 3, compared to Case 1 and Case 2. Although the profit in Case 2 is higher, compared to Case 3, it should be noted

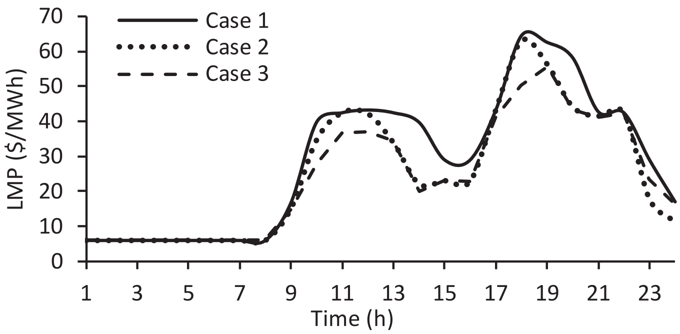

Fig. 5. Energy market clearing price, LMP at bus-18.

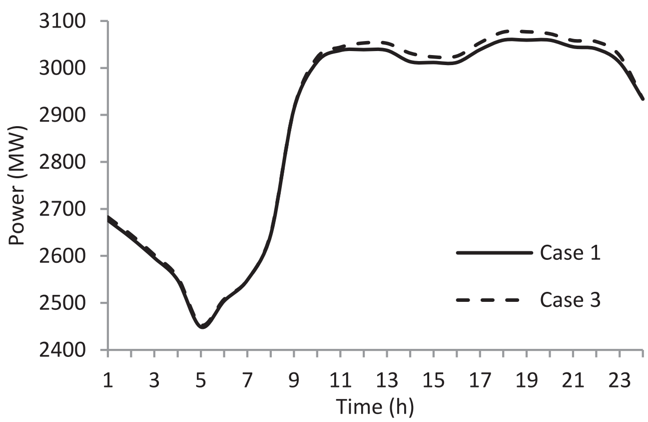

Fig. 6. Generation dispatch over 24 hours in Case 1 and Case 3.

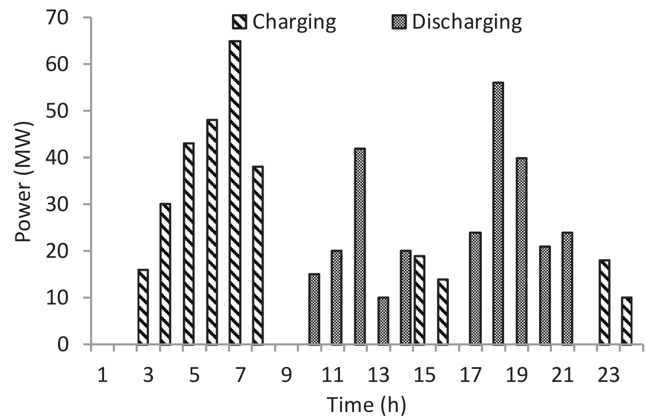

Fig. 7. Aggregate charging/discharging after market dispatch in Case 3.

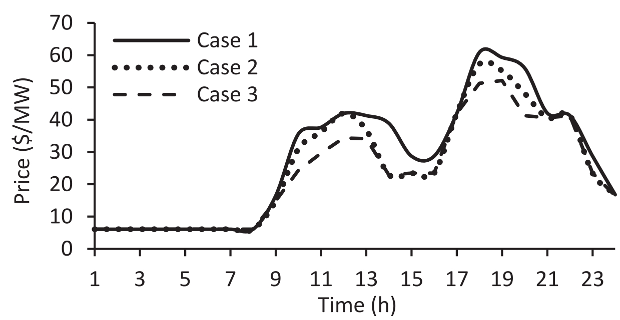

Fig. 8. Spinning reserve market clearing price.

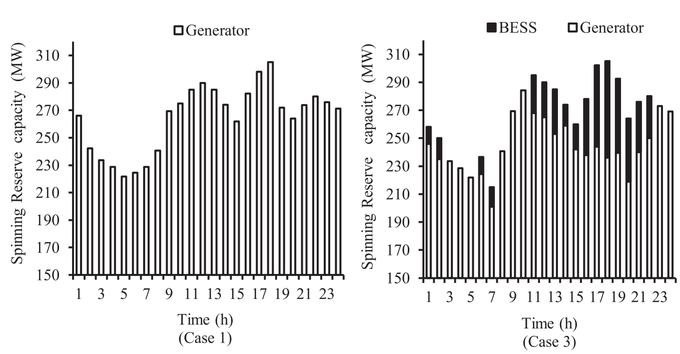

Fig. 9. Spinning reserve contracted over 24 hours in Case 1 and Case 3.

that Case 3 correctly captures the actual cost of BESS operation, accounting for its degradation, thus providing realistic market clearing decisions, from the view point of both the ISO and BESS owners.

Fig. 5 shows the LMPs at bus-18 for the three cases; the LMP reduces during the two peak periods (hours 10–16 and 18–20) in Case 2 & 3 because of the cheaper BESS charging offers in the energy market. The reduction is more significant (upto 44% at hour-14 and 29% at hour-18) in Case 3. Thus, it is noted that BESS can play a vital role in stabilizing the market prices.

It is noted from Fig. 6 that in Case 3 the dispatched generation is slightly higher than in Case 1 during the hours 11-20. This is because there is a slight increase in the cleared demand during these hours as a result of BESS participation with lower priced discharge offers.

Fig. 7 shows the aggregated charging and discharging power from all BESS units, in Case 3 on an hourly basis. It is noted that BESS charging takes place mainly during the off peak hours 3–8, while the discharging occurs mainly during the peak hours 11–12 and 17–21, thus resulting in an increased benefit for the BESS owners from energy arbitrage.

The SOC profiles of randomly chosen five BESS units in Case 3 are shown in Fig. 10. It is noted that the BESS units have varying charging and discharging profiles because of their locational placement and the variations in theirs cost components which determine their market clearance and dispatch.

It is noted that the spinning reserve prices (Fig. 8) in Case 3, the spinning reserve prices are significantly reduced in hours 10–16 and 18–20, because the cheaper offers from BESS have replaced some of the expensive generator offers in Case 1.

Fig. 9 shows the contracted spinning reserve capacity in Case 1 (from generators only) and Case 3 (from generators and BESS). It is noted that in Case 3, while the generators provide the significant share of the spinning reserve requirements, BESS is able to provide about 10% of system spinning reserve requirement and thus providing more options to the ISO. Furthermore, it is interesting to note that the BESS provides spinning reserve during charging operations also (hours 1, 2, 6, and 7) apart from the discharging operation hours, which may be perceived as a demand response provision.

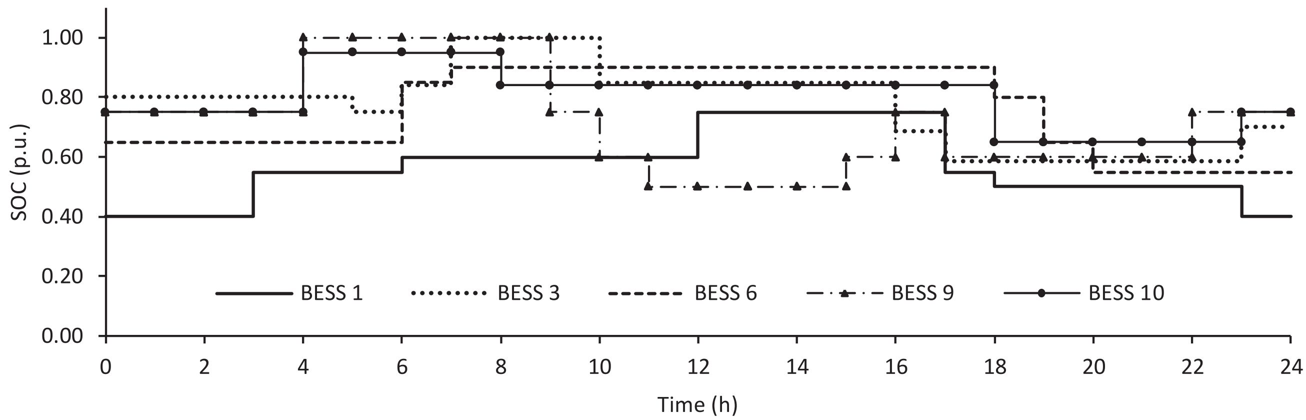

Fig. 10. SOC profiles of BESS after market dispatch in Case 3.

TABLE III
SOLVER AND MODEL STATISTICS FOR THREE CASES

	Case 1	Case 2	Case 3
Model type	MIP	MIP	MIP
Solver Used	CPLEX	CPLEX	CPLEX
Single equations	673,261	675,829	677,591
Single variables	413,257	414,653	415,613
CPU time, s	152	167	179

A. Computational Aspects

The proposed market model is solved using CPLEX solver (12.1.0) [42] which is suitable for mixed integer programming (MIP) problems. The 24 bus RTS is programmed and executed on a Dell PowerEdge R810 server, in GAMS (23.3.3) environment [43], Windows 64-bit operating system, with 4 Intel-Xeon 1.87 GHz processors and 64 GB of RAM. The model and solver statistics for the three cases are given in Table III.

VI. CONCLUSION

This paper, has proposed a novel BESS operational cost function model considering degradation cost, based on depth of discharge and discharge rate. The model was developed considering Lithium-ion batteries, and the approach can be applied to other conventional electrochemical batteries such as lead acid, nickel-based, *etc.*,) but not flow batteries. A detailed charging bid and discharging offer structure based on the proposed operational cost functions was formulated. Subsequently, a new framework and mathematical model for BESS participation in an LMP based co-optimized energy and spinning reserve market was developed. The effectiveness of the BESS inclusive market model was validated on the IEEE RTS and compared with two other realistic market structures: (a) traditional structure with only generator and load participation (b) BESS bidding as the generator/load with price quantity pair. BESS participation using the proposed operational cost function and bid/offer structure resulted in a higher social welfare than when no BESS was present or with a simple bid/offer structure for BESS, based on market price expectations. The participation of BESS also reduced energy and spinning reserve prices when it provided services in the energy and spinning reserve markets. Overall, the inclusion of BESS in the electricity markets has resulted in improving the economic and technical benefits for the ISO by providing more options for system operation.

The advantages of the proposed work are that: (i) it correctly captured the actual cost of BESS operation, accounting for its degradation, thus providing realistic market clearing decisions, (ii) it appropriately met the important requirement of FERC Order 841 to develop a participation model for ESS, accounting for their physical and operational characteristics such as the SOC, discharge rate, etc., in the ESS bidding parameters, to facilitate their participation in ISO markets.

REFERENCES

[1] International Renewable Energy Agency (IRENA), "Electricity storage and renewables: Costs and markets to 2030," Tech. Rep., Oct. 2017. [Online]. Available: http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IR ENA_Electricity_Storage_Costs_2017.pdf

[2] Federal Energy Regulatory Commission (FERC), "Electric storage participation in markets operated by regional transmission organizations and independent system operators," Tech. Rep., Feb. 2018. [Online]. Available: https://www.ferc.gov/whats-new/comm-meet/2018/021518/E-1.pdf

[3] Electric Power Research Institute (EPRI), "Independent system operator and regional transmission organization energy storage market modeling working group white paper: Current state of the art in modeling energy storage in electricity markets and alternative designs for improved economic efficiency and reliability," Tech. Rep., Mar. 2018. [Online]. Available: https://www.epri.com/#/pages/product/000000003002012327/?lang=en-US

[4] New York Independent System Operator (NYISO), "Energy storage market design update," Tech. Rep., Jul. 2018. [Online]. Available: https://www.nyiso.com/documents/20142/2547799/ESR%20Market%20Design%20Update.pdf/003cc522-386f-13ba-aa1b-72146c572dee

[5] California ISO (CAISO), "Business practice manual for market operation," Tech. Rep., Nov. 2018. [Online]. Available: https://bpmcm.caiso.com/BPM%20Document%20Library/Market%20Operations /BPM_for_Market%20Operations_V58_redline.pdf

[6] ISO New England (ISONE), "Energy Storage Device Project," Tech. Rep., Nov 2018. [Online]. Available: https://www.iso-ne.com/participate/support/customer-readiness-outlook/e sd-project#project-overview-4

[7] IESO, "IESO report: Energy storage," Tech. Rep., Mar. 2016. [Online]. Available: http://www.ieso.ca/en/Sector-Participants/Energy-Procurement-Programs-and-Contracts/Energy-Storage

[8] PJM, "Q&A for electric storage resource participation model," Tech. Rep., Feb. 2019. [Online]. Available: https://pjm.com/-/media/committees-groups/committees/mic/20190206/20190206-item-07c-faq-for-order-841-and-hybrids.ashx

[9] PJM, "Order 841: Status quo in PJM," Tech. Rep., May 2018. [Online]. Available: https://www.pjm.com/-/media/committees-groups/committees/mic/20180510-special-electric/20180510-item-03a-esr-841-status-quo-review.ashx
[10] PJM, "Current rules for electric storage resources," Tech. Rep., May 2018. [Online]. Available: https://https://www.pjm.com/-/media/committees-groups/committees/mic/20180510-special-electric/20180510-item-03b-all-manual-citing-of-esr-status-quo.ashx
[11] PJM, "Electric storage resources participation model: PJM compliance for order 841," Tech. Rep., Dec. 2018. [Online]. Available: https://www.pjm.com/-/media/committees-groups/subcommittees/irs/20181210/20181210-item-10-ferc-filing-on-energy-storage-integration-in-pjm-markets.ashx
[12] C. Martinez, R. Behnke, and X. Zhang, "Impacts of energy storage on short term operation planning under centralized spot markets," *IEEE Trans. Smart Grid*, vol. 5, no. 2, pp. 1110–1118, Mar. 2014.
[13] N. Li, C. Uckun, E. Constantinescu, and A. Bottereud, "Flexible operations of batteries in power system scheduling with renewable energy," *IEEE Trans. Sustain. Energy*, vol. 7, no. 2, pp. 685–696, Apr. 2016.
[14] R. Jiang, J. Wang, and Y. Guan, "Robust unit commitment with wind power and pumped storage hydro," *IEEE Trans. Power Syst.*, vol. 2, no. 2, pp. 800–810, May 2012.
[15] B. Lu and M. Shahidehpour, "Short-term scheduling of battery in a grid-connected PV/battery system," *IEEE Trans. Power Syst.*, vol. 20, no. 2, pp. 1053–1061, May 2005.
[16] J. G. Gonzalez, R. M. Muela, L. Santos, and A. Gonzalez, "Stochastic joint optimization of wind generation and pumped-storage units in an electricity market," *IEEE Trans. Power Syst.*, vol. 23, no. 2, pp. 460–468, May 2008.
[17] H. Ding, Z. Hu, and Y. Song, "Rolling optimization of wind farm and energy storage system in electricity markets," *IEEE Trans. Power Syst.*, vol. 30, no. 5, pp. 2676–2684, Sep. 2015.
[18] A. A. Thatte, L. Xie, D. E. Viassolo, and S. Singh, "Risk measure based robust bidding strategy for arbitrage using a wind farm and energy storage," *IEEE Trans. Smart Grid*, vol. 4, no. 4, pp. 2191–2199, Dec. 2013.
[19] H. Ding, P. Pinson, and Z. Hu, "Integrated bidding and operating strategies for wind-storage systems," *IEEE Trans. Sustain. Energy*, vol. 7, no. 1, pp. 163–173, Jan. 2016.
[20] D. Pudjianto, M. Aunedi, P. Djapic, and G. Strbac, "Whole-systems assessment of the value of energy storage in low-carbon electricity systems," *IEEE Trans. Smart Grid*, vol. 5, no. 2, pp. 1098–1109, Mar. 2014.
[21] H. Hejazi and H. Rad, "Optimal operation of independent storage systems in energy and reserve markets with high wind penetration," *IEEE Trans. Smart Grid*, vol. 5, no. 2, pp. 1088–1097, Mar. 2014.
[22] M. Kazemi, H. Zareipour, N. Amjadi, and W. D. Rosehart, "Operation scheduling of battery storage systems in joint energy and ancillary services markets," *IEEE Trans. Sustain. Energy*, vol. 8, no. 4, pp. 1726–1735, Oct. 2017.
[23] E. Nasrolahpour, J. Kazempour, H. Zareipour, and W. D. Rosehart, "A bilevel model for participation of a storage in energy and reserve markets," *IEEE Trans. Sustain. Energy*, vol. 9, no. 2, pp. 582–598, Apr. 2018.
[24] B. Xu, T. Zheng, E. Litinov, and D. S. Kirschen, "Scalable planning for energy storage in energy and reserve markets," *IEEE Trans. Power Syst.*, vol. 32, no. 2, pp. 1634–1642, Mar. 2017.
[25] H. Pandzic, Y. Dvorkin, and M. Carrin, "Investments in merchant energy storage: Trading-off between energy and reserve markets," *Appl. Energy*, vol. 230, no. 2, pp. 277–286, Apr. 2018.
[26] H. M. Rad, "Optimal bidding, scheduling, and deployment of battery systems in California day-ahead energy market," *IEEE Trans. Power Syst.*, vol. 31, no. 1, pp. 2248–2259, Jan. 2016.
[27] I. Duggal and B. Venketesh, "Short-term scheduling of thermal generators and battery storage with depth of discharge-based cost model," *IEEE Trans. Power Syst.*, vol. 30, no. 4, pp. 2110–2118, Jul. 2015.
[28] B. Xu, T. Zheng, E. Litinov, and D. S. Kirschen, "Factoring the cycle aging cost of batteries participating in electricity markets," *IEEE Trans. Power Syst.*, vol. 33, no. 2, pp. 2248–2259, Mar. 2018.
[29] G. He, Q. Chen, C. Kang, P. Pinson, and Q. Xia, "Optimal bidding strategy of battery storage in power markets considering performance-based regulation and battery cycle life," *IEEE Trans. Smart Grid*, vol. 7, no. 5, pp. 2359–2367, Jul. 2016.
[30] B. Xu, Y. Shi, E. Litinov, D. S. Kirschen, and B. Zhang, "Optimal battery participation in frequency regulation markets," *IEEE Trans. Power Syst.*, vol. 33, no. 6, pp. 6715–6725, Mar. 2018.
[31] J. Vetter *et al.*, "Ageing mechanisms in lithium-ion batteries," *J. Power Sources*, vol. 147, pp. 269–281, Mar. 2005.
[32] M. A. Ortega-Vazquez, "Optimal scheduling of electric vehicle charging and vehicle-to-grid services at household level including battery degradation and price uncertainty," *IET Gener. Transmiss. Distribution*, vol. 8, no. 6, pp. 1007–1016, Nov. 2014.
[33] MISO, "MISO: FERC electric tariff," Tech. Rep., Nov. 2013. [Online]. Available: https://cdn.misoenergy.org/Module%20C108024.pdf
[34] Northern Arizona Wind & Sun, Inc., "Northern Arizona Wind & Sun, Inc. battery cycles vs. lifespan plot," Tech. Rep., Oct. 2018. [Online]. Available: https://www.solar-electric.com/learning-center/batteries-and-charging/d eep-cycle-battery-faq.html#Cycles%20vs%20Life
[35] C. Zhou, K. Qian, and W. Zhou, "Modeling of the cost of EV battery wear due to V2G application in power systems," *IEEE Trans. Energy Convers.*, vol. 26, no. 4, pp. 1041–1050, Dec. 2011.
[36] J. Wang *et al.*, "Degradation of lithium ion batteries employing graphite negatives and nickele-cobalt-manganese oxide + spinel manganese oxide positives: I, aging mechanism & life estimation," *J. Power Sources*, vol. 269, pp. 937–948, Jul. 2014.
[37] F. Bouffard and F. Galiana, "An electricity market with a probabilistic spinning reserve criterion," *IEEE Trans. Power Syst.*, vol. 19, no. 1, pp. 300–307, Aug. 2004.
[38] V. Algar, "Understanding battery life Vanadium Redox flow batteries," VSUN Energy, Tech. Rep., May 2017. [Online]. Available: https://www.australianvanadium.com.au/wp-content/uploads/2018/11/VSUN-Energy-presentation-final.pdf
[39] N. Padmanabhan, M. Ahmed, and K. Bhattacharya, "Simultaneous procurement of demand response provisions in energy and spinning reserve markets," *IEEE Trans. Power Syst.*, vol. 33, no. 5, pp. 4667–4682, Sep. 2018.
[40] A. Motto, F. D. Galiana, A. Conejo, and J. Arroyo, "Network-constrained multi period auction for a pool-based electricity markets," *IEEE Trans. Power Syst.*, vol. 17, pp. 646–1653, Aug. 2002.
[41] C. Grigg *et al.*, "The IEEE Reliability Test System—1996. A report prepared by the Reliability Test System Task Force of the Application of Probability Methods Subcommittee," *IEEE Trans. Power Syst.*, vol. 14, no. 4, pp. 1010–1020, Aug. 1999.
[42] GAMS, "GAMS–The solver manuals," Tech. Rep., Oct. 2015. [Online]. Available: http://www.gams.com/help/topic/gams.doc/solvers/allsolvers.pdf
[43] R. E. Rosenthal, "GAMS–A user's guide," Tech. Rep., May 2015. [Online]. Available: http://www.gams.com/dd/docs/bigdocs/GAMSUsersGuide.pdf

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