Optimal Scheduling of Merchant-Owned Energy Storage Systems with Multiple Ancillary Services

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***Abstract*—Energy storage systems can provide a set of benefits to improve the flexibility and reliability of electric power systems. They could supply a set of different services at the same time. In this context, this paper proposes a new linear profit-maximizing formulation for grid-connected merchant-owned energy storage systems with multiple ancillary services. All technical characteristics of ESS have been modelled including cycle life loss due to fast charge/discharge and low depth of discharge operations. A piece-wise linear model of an ESS converter's capability curve has been included.**

The proposed model of ESS could gain revenues from five services: voltage regulation, frequency regulation, energy arbitrage, reserve power and black start. The model was assessed considering a battery ESS, a flywheel ESS and a compressed air ESS using Ontario energy market price data, and the results demonstrate the benefits of the formulation. From the base case study and sensitivity studies, it is clear that the merchant-owned battery ESS and the flywheel ESS can generate profits, especially from voltage regulation and frequency regulation services. The compressed air ESS is not profitable for the considered price data. The case studies prove that the proposed model can be used as an optimal planning and operation tool for any type/size of ESS.

***Index Terms*—Energy Storage, Ancillary Markets, Energy Storage Scheduling**

I. Nomenclature

A. Acronyms

DOD	Maximum depth of discharge of the ESS operation
ESS	Energy storage systems
SOC	State of charge of the ESS

B. Indices

i	Index for denoting sections of the cycle life vs DOD curve
q	Index for denoting quarters
t	Index for denoting hourly time periods of the year, t = 1 : NT

C. Parameters

A_q	Factor for distributing cost for all quarters of all years
c_1, c_2, c_3	Constants for representing operation and maintenance cost equation
c_4	Constant for representing lifetime reduction due to overcharging
CEC	Cost of energy storage for installing a unit of energy storing capacity ($/MWh)
D	Per hours self-discharge rate
EFF	Charge/discharge efficiency
KC, KD	Constants of NC vs SOC curve
Kcc_1, Kcc_2	Constants of the linearizing of the inverter's capability curve
KFR	Energy requirement to supply 1 MW of frequency regulation power (MWh)
KRP	Energy requirement to supply 1 MW of reserve power (MWh)
M	A large number to model the constraint
$\overline{NC}$	Maximum energy storage cycle life (number of cycles)
NS	Number of sections of cycle life vs depth of discharge curve
NQ	Rated lifetime of the battery (quarters)
NT	Number of hours in the year
$\overline{P}, \underline{P}$	Rated charge/discharge power of the ESS converter (MW)
PAR_t	Activated reserve power (MW)
$\overline{PS}, \underline{PS}$	Rated charge/discharge power of the ESS storage unit (MW)
rBS	Price of black start ancillary service contract ($/MW)
rEA_t	Price of energy arbitrage in each hour ($/MW)
rFR	Price of frequency ancillary service contract ($/MW)
rRP_t	Price of reserve power in each hour ($/MW)
rVR	Price of voltage regulation ancillary service contract ($/MW)
$\overline{SE}$	Rated maximum ESS energy level (MWh)

Financial support: This work was supported in part by the IESO and NSERC grants awarded to B. Venkatesh. C. Opathella, A. Adel, A. Elkasrawy and B. Venkatesh are with the Centre for Urban Energy, Ryerson University, Toronto, ON, M5B 2K3, Canada (e-mail: opathella@ryerson.ca).

$\underline{\underline{SE}}$	Safe minimum ESS energy level (MWh)
SE_R	Residual Energy capacity after maximum cycling $\overline{NC}$ (MWh)
SE_{FR}	Value of SOC for frequency regulation (MWh)

D. Decision variables

ADC	Assets depreciation cost due to charge/discharge cycles ($)
AIC	Annualized investment cost ($)
IC	Total investment cost ($)
$B1_i$	Binary variables to select linearized sections of nonlinear curve of NC vs SOC
$B2_q$	Binary variable for representing end of life quarter
ΔNC	Cycle life reduction due to fast charging or fast discharging (number of cycles)
$\Delta P1$, $\Delta P2$	Discharging and Charging power beyond the specified value (MW)
NC	Number of charge/discharge cycles within a year
OMC	Operation and maintenance cost ($)
PBS	Contracted power for black start service (MW)
PFR	Contracted power for frequency regulation (MW)
PEA_t	Energy arbitrage power for each hour (MW)
PL	Total power loss (MW)
PL^-, PL^+	Power loss at charging and discharging (MW)
PRP_t	Reserve power for each hour (MW)
QVR	Contracted reactive power for voltage regulation (MVAr)
RV_{EA}	Revenue energy arbitrage ($)
RV_{VR}	Revenue from voltage regulation ancillary service contract ($)
RV_{RP}	Revenue from reserve power ($)
RV_{BS}	Revenue from black start ancillary service contract ($)
SE_t	ESS energy level at each hour (MWh)
$\underline{SE}$	Energy level which affects the lifetime degradation of the ESS. This is the energy level at the depth of discharge (DOD) (MWh).

II. Introduction

ENERGY storage systems (ESS) constitute one of the most promising research areas in modern power systems. Enthusiasm for energy storage has been rekindled recently due to the following factors: the ability of ESS to support the integration of intermittent renewable energy resources (REs), depletion of non-renewable energy sources, advancements of ESS technologies, improvements in deregulated energy markets including ancillary services markets, difficulties of siting new transmission and distribution facilities, etc.

The intermittent nature of REs is a barrier to having a high penetration of REs in power systems. ESS can support the integration of REs by storing the generated energy of REs at times of off-peak electricity demand and then releasing it for use during peak demand periods. In other words, ESS help to increase the penetration of intermittent REs in power systems by shifting REs outputs from low demand periods to high demand periods. Besides that, ESS also can provide a set of ancillary services for power systems such as voltage regulation support, frequency regulation support, ramp power support, and power system restoration or black start [1], [2]. ESS are one of the first options that planners can select due to the flexibility that ESS can provide for power system operation. However, the high investment cost of ESS has limited its widespread adoption.

In the literature, several efforts have been made to study the technical and economic aspects of ESS. First, in the context of technical benefits, more than twenty-six applications for using ESS in power system support were mentioned in [1] such as transmission congestion relief, load following, and transmission and distribution upgrade deferral, to name a few. In [2], some applications are reported which have great potential value from Southern California Edison’s perspective. In the context of power system support, ESS have been employed for providing several ancillary services in [3] - [10]. In [3] - [5], a coordinated control algorithm was proposed to mitigate frequency and voltage deviation by distributed ESS. The proposed algorithm in [3], was applied to a real Korean distribution system and showed better performance than the existing uncoordinated control scheme with on-load tap changer. In [4], a control scheme for PV inverter and ESS was proposed based on intelligent adaptive neuro-fuzzy inference systems (ANFIS). The scheme controls both the PV inverter and the ESS to regulate the voltage at the point of common coupling. The authors of [5] have proposed a control method to coordinate the operation of distributed ESS in low-voltage distribution networks with high penetration of PV.

ESS operation for Frequency Regulation (FR) control strategies is presented in [3], and [6] - [8]. The State of Charge (SOC) of ESS is maintained in the optimal range to slow down battery ageing. These strategies are validated using data of German and PJM regulation markets. In [7], a strategy for the sizing of frequency regulation aggregated ESS was proposed. The strategy depends on the inertia constant and the power/frequency characteristics of the power system. In addition, a dynamic simulation for incorporating ESS into frequency regulation of a wind-diesel system was proposed in [8].

System restoration and black start support of ESS are discussed in [9] and [10]. A bi-level network reconfiguration optimization model has been developed to reveal the restoration paths with the support of centralized charging stations for electric vehicles in [9]. Also in [10], a multi-objective optimization model for power system restoration with ESS operation strategy is proposed.

Economic assessments of ESS for supplying the above services have been presented in [11] - [16]. The authors in [11] have developed a two-level profit-maximizing model for merchant-owned battery ESS which is used for frequency regulation ancillary service. The model minimizes the operating cost by keeping SOC in an optimal range. Several other studies have been conducted to assess the energy arbitrage benefit of ESS [12] - [15]. An energy arbitrage profit-maximizing model of EES for the Nordic power market is described in [12]. The authors in [13] have examined the economics of two emerging ESS technologies for energy arbitrage with respect to historical New York electricity market prices. The authors in [14] have proposed a stochastic formulation, also for energy arbitrage profit maximization. Price uncertainty in the day-ahead and real-time markets has a significant impact on energy arbitrage profit. The model has been examined using realistic market price data and shows better performance than the deterministic scheduling [14]. Another stochastic model for energy arbitrage of battery ESS has been developed in [15], considering varying prices, varying battery lifetime and varying operating performance.

In addition, there are some studies that consider the reserve power benefits of ESS. A mixed-integer model of daily reserve scheduling of pumped-storage hydropower plants is presented in [16]. Also in [17], a weekly reserve power scheduling method for the scheduling of pumped-storage hydro and battery ESS is described. The ESS is scheduled based on the predicted generation of the renewable energy units. A stochastic two-stage day-ahead unit commitment model for the incorporation of solar and wind power plants with thermal ESS to meet the reserve requirements is proposed in [18].

Motivation for this work

The research studies reviewed above consider the profit-maximization of ESS, but they have two major limitations: (1) the complexity of formulations due to the nonlinear ESS characteristics, and (2) the models are limited to a specific ESS technology and ESS which supply one or two ancillary services. There is a need for a generic model which can analyze the profitability of any type/size of ESS with all possible supply levels of ancillary services. The model should optimize the supply level of each ancillary service based on ESS characteristics and market price.

Proposed Work

In this paper, we propose a novel linear profit-maximizing model of ESS. The proposed generic model is applicable to any technology type of ESS and can consider multiple ancillary services for the ESS operation. The proposed model considers that ESS could participate in the following ancillary services: voltage regulation, frequency regulation, reserve power, energy arbitrage, and black start support. This paper addresses key concerns of ESS owners with respect to maintaining optimal operation of their units and gaining maximum profits. Furthermore, the proposed model looks at the abuse of ESS and related costs to maximize profit.

This paper is organised as outlined below. Section III presents the mathematical problem formulation of maximizing the overall profit of ESS operation. In Section IV, results of a case studies and sensitivity analyses are explained. Section V summarizes the benefits of the proposed merchant-owned ESS scheduling model. The conclusion of the paper is in Section VI.

III. Maximizing Overall Profit of ESS Operation for Several Ancillary Services

This section presents the details of the problem formulation of maximizing the overall profit of ESS operation with multiple ancillary services.

A. Problem Statement

The problem is stated as maximizing the net profit, which is defined as the difference between the revenues of all ancillary services which ESS can provide and the total cost of ESS. The problem considers revenues from five services: voltage regulation support, frequency regulation support, reserve power, energy arbitrage, and black start support. In addition, the study considers the ESS cost as threefold: the investment cost, the operation and maintenance cost and the asset depreciation cost. The optimization problem is subject to the techno-economic constraints which ensure the feasibility of ESS operation.

B. Problem Formulation

1) Objective function

$$\text{Maximize} \ \left(RV_{FR}+RV_{EA}+RV_{VR}+RV_{PR}+RV_{BS} - OMC - AIC - ADC \right) \quad (1)$$

The first five terms of the objective function are the revenues from frequency regulation, energy arbitrage, voltage regulation, reserve power and black start support. They can be written as follows (2) – (6).

$$RV_{FR}= rFR \cdot PFR \quad (2)$$

$$RV_{EA}=\sum_{t=1}^{NT} rEA_t \cdot (PEA_t+PAR_t) \quad (3)$$

$$RV_{VR}= rVR \cdot QVR \quad (4)$$

$$RV_{PR}=\sum_{t=1}^{NT} rRP_t \cdot PRP_t \quad (5)$$

$$RV_{BS}= rBS \cdot PBS \quad (6)$$

The remaining three terms are cost values with respect to operation and maintenance cost, annualised investment cost and asset depreciation cost of the ESS. They can be written as follows in (7) – (9). In (7), the fixed operation and maintenance cost is c_3. The power loss (PL) increases the cooling requirement and increases the operation cost. The operation and maintenance cost also increases due to high use (cycling) of the ESS.

$$OMC= c_1 \cdot NC + c_2 \cdot \sum_{t=1}^{NT} PL_t + c_3 \quad (7)$$

The annualised investment cost is distributed for each quarter throughout the ESS lifespan. The sum of the cost over four quarters gives the annual cost. Quarterly costs were considered for more accurate results based on lifetime loss of ESS.

$$\mathrm{AIC} = \mathrm{IC} \times 4 \cdot \sum_{q=1}^{NQ} A_q \times B2_q \qquad (8)$$

The ADC considers the depreciation of the asset value due to the degradation of energy storing (MWh) capacity. In most types of ESS, this is negligible. However, in battery technologies, this could be a considerable ESS cost item. It is assumed that the energy capacity is linearly related to the number of cycles operated within a year.

$$\mathrm{ADC} = \left[\frac{(\overline{\mathrm{SE}} - \mathrm{SE_R})}{\overline{\mathrm{NC}}} \cdot \mathrm{CEC} \right] \cdot \mathrm{NC} \qquad (9)$$

2) Constraints

The intertemporal power and energy relationship:

An ESS consists of an electric converter and a storage unit (Fig. 1 (a)). The storage unit has an intertemporal relationship between the charge/discharge power and the stored power [26]. It can be written as follows (10). Self-discharge is normally a nonlinear relationship between the losses and energy [28] - [29] (Fig. 1 (b)). In (10), the hourly self-discharge rate is denoted as D.

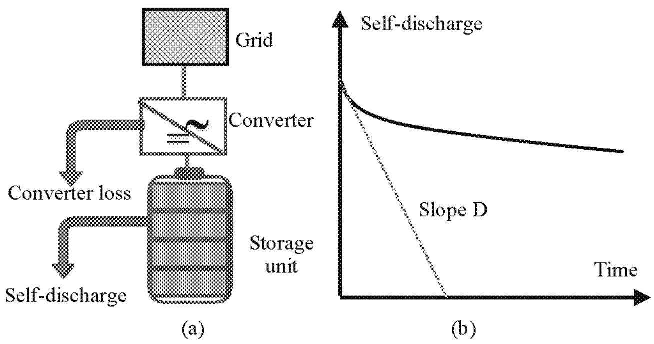

Fig. 1. Self-discharge and converter loss of the storage unit [28] - [29].

$$(1 - D) \cdot \mathrm{SE}_{t-1} - \mathrm{SE}_t - \mathrm{SE_{FR}} = (\mathrm{PEA}_t + \mathrm{PAR}_t + \mathrm{PL}_t) \cdot 1 \text{ hour} \quad \forall\, t \qquad (10)$$

PAR is the activated reserve power. If the ESS operator has a forecast for PAR, it can be used for the analysis. Otherwise, it can be zero. If the ESS contracts to supply frequency regulation, $\mathrm{SE_{FR}}$ represents the value of energy used at each hour for supplying frequency regulation. Reserve power and black start support do not need energy unless they are called upon. Therefore, they are not included in (10). However, the ESS always should maintain enough energy to supply black start support. Furthermore, it should also maintain the ability to deliver and absorb energy in order to supply reserve power and frequency regulation ancillary services (11).

$$\left[\underline{SE} + SE_{BS} + SE_{RP} + SE_{FR}\right] \leq \mathrm{SE}_t \leq \left[\overline{SE} - SE_{RP} - SE_{FR}\right] \qquad (11)$$

Frequency regulation power and energy relationship

Ideally frequency regulation is a zero-energy required service. This means that in the long-run, energy required for the random charging and discharging function of frequency regulation is negligible. However, in practice, a certain level of energy needs to be maintained. This constraint considers the linear dependency between the power and energy values of frequency regulation ancillary service [26]. The relation is based on the constant KFR which depends on the type of the selected technology of ESS as given in (12).

$$\mathrm{SE_{FR}} = \mathrm{KFR} \cdot \mathrm{PFR} \qquad (12)$$

Reserve power and energy relationship

The linear relationship between the power and energy values of reserve power ancillary service [26] is presented in (13). The constant, KRP depends on the type of the selected ESS technology. In this formulation $\mathrm{PRP_t}$ is a positive value, even though the ESS agrees to be a positive or a negative reserve power.

$$\mathrm{SE_{RP_t}} = \mathrm{KRP} \cdot \mathrm{PRP_t} \qquad (13)$$

Power loss

There is a power loss in the power converter. This could be either power electronic switching and resistances loss of the converter of the battery ESS or generator/motor loss of a pumped-hydro ESS. It is expressed based on the overall charging and discharging efficiency of the converter (14).

$$PL^{+}_{t} + PL^{-}_{t} = (1\text{-EFF}) \cdot (PEA_t + PAR_t) \qquad (14a)$$

$$PL^{+}_{t} \geq 0 \qquad (14b)$$

$$PL^{-}_{t} \leq 0 \qquad (14c)$$

$$\mathrm{PL_t} = PL^{+}_{t} - PL^{-}_{t} \qquad (14d)$$

Converter capability curve:

Fig. 2 shows the typical capability curve of an ESS's electricity converter during charging and discharging. This nonlinear relationship between the active and reactive power is given in [19]. The approximate linearized curve shown in dashed-black is presented using (15) – (20). The capability curve of the generator/motor can also be modelled as explained below.

$$\mathrm{PEA_t} + \mathrm{PRP_t} + \mathrm{PFR} + \mathrm{Kcc_1} \cdot \left(\overline{\mathrm{P}}/\underline{\mathrm{QVR}}\right) \cdot \mathrm{QVR} \leq \mathrm{Kcc_2} \cdot \overline{\mathrm{P}} \qquad (15)$$

$$\mathrm{PEA_t} + \mathrm{PRP_t} + \mathrm{PFR} + \mathrm{Kcc_1} \cdot \left(\overline{\mathrm{P}}/\overline{\mathrm{QVR}}\right) \cdot \mathrm{QVR} \leq \mathrm{Kcc_2} \cdot \overline{\mathrm{P}} \qquad (16)$$

$$\mathrm{PEA_t} - \mathrm{PRP_t} - \mathrm{PFR} + \mathrm{Kcc_1} \cdot \left(\underline{\mathrm{P}}/\overline{\mathrm{QVR}}\right) \cdot \mathrm{QVR} \geq \mathrm{Kcc_2} \cdot \underline{\mathrm{P}} \qquad (17)$$

$$\mathrm{PEA_t} - \mathrm{PRP_t} - \mathrm{PFR} + \mathrm{Kcc_1} \cdot \left(\underline{\mathrm{P}}/\underline{\mathrm{QVR}}\right) \cdot \mathrm{QVR} \geq \mathrm{Kcc_2} \cdot \underline{\mathrm{P}} \qquad (18)$$

$$\mathrm{PEA_t} + \mathrm{PRP_t} + \mathrm{PFR} \leq \overline{\mathrm{P}} \qquad (19)$$

$$\mathrm{PEA_t} - \mathrm{PRP_t} - \mathrm{PFR} \geq \underline{\mathrm{P}} \qquad (20)$$

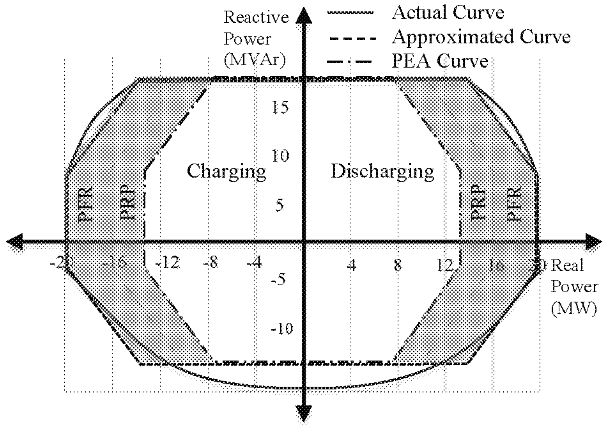

Fig. 2. Typical inverter capability curve during charging and discharging [19]

Storage unit fast charge/discharge power

In addition to the converter capability curve limits, storage units have power limits based on the state of charge Fig. 3. This is a significant limiting factor in batteries. Fast charge/discharge beyond these limits could shorten cycle life of the storage unit [27]. The constraints (21) and (22) estimate the value of fast charge/discharge beyond the rated power in each hour. The total discharge power can be more than the rated power of the storage unit by choosing a negative value for $\Delta P1$ (21). This allows fast discharge higher than the rated power.

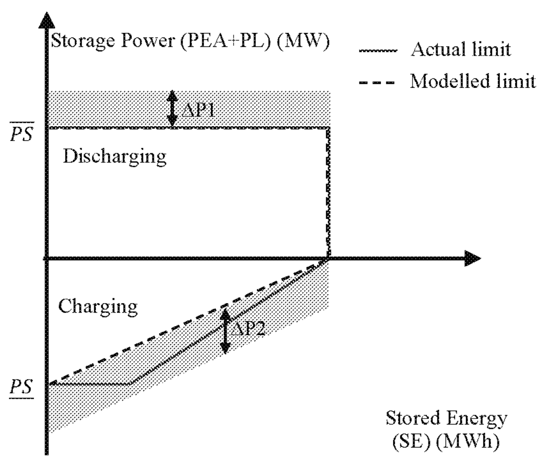

Fig. 3. Storage unit charging/discharging power limits [30]

$$PEA_t + PAR_t + PL_t + PFR + \Delta P1_t \leq \overline{PS} \tag{21a}$$

$$\Delta P1_t \leq 0 \tag{21b}$$

The fast charge beyond the recommended limit is expressed as in (22). Unlike the maximum discharge power, the ESS maximum charge power is not a constant. It depends on the ESS energy level (State of Charge). For example, at high SOC levels, a storage unit needs to be charged at low power. For this study, it is assumed that the maximum charge power is a linear function of the ESS energy level (right-hand side of (22a)) Fig. 3.

$$PEA_t - PAR_t + PL_t - PFR + \Delta P2_t \geq -\left(\underline{PS}/\overline{SE}\right) \cdot SE_t + \underline{PS} \tag{22a}$$

$$\Delta P2_t \geq 0 \tag{22b}$$

The number of operation cycles: The formula for the number of operation cycles of ES is given in [24]. For the study, the simplified equation (23) is used here.

$$NC = \left(\sum_{t=1}^{NT} \max\{SE_{t-1} - SE_t , 0\} \right) \Big/ \overline{SE} \tag{23}$$

Cycle life reduction due to fast charge/discharge

As stated in [27], the cycle life could be affected by fast charge and discharge processes. The constraint (24) considers the effects of fast charge/discharge on the cycle life. It is a linear approximation of the relationship between the cycle life reduction and the fast charge/discharge power values over a year.

$$\Delta NC = KP_b \cdot \sum_{t=1}^{NT} (\Delta P2_t - \Delta P1_t) \tag{24}$$

Computing energy level of depth of discharge ($\underline{SE}$):

In battery ESS, the depth of discharge (DOD) could reduce the cycle life of the ESS [25]. The ESS operator can select the depth of discharge or the relevant low energy level ($\underline{SE}$). The energy level at each hour should be higher than the selected low energy level (25) (Fig. 4).

$$SE_t \geq \underline{SE} \tag{25}$$

Number of cycles and $\underline{SE}$ energy level relationship

In this study, the nonlinear curve in [24] is linearized considering NS number of linear sections. The constraint (26) considers the cycle life reduction due to low $\underline{SE}$.

$$\overline{NC} = \sum_{i=1}^{NS} KC_i \cdot \underline{SE}_i + \sum_{i=1}^{NS} B1_i \cdot KD_i \tag{26a}$$

$$B1_i \cdot SE_i \leq \underline{SE}_i \leq B1_i \cdot SE_{i+1} \quad i = 1 \text{ to } NS \tag{26b}$$

$$\sum_{i=1}^{NS} B1_i = 1 \tag{26c}$$

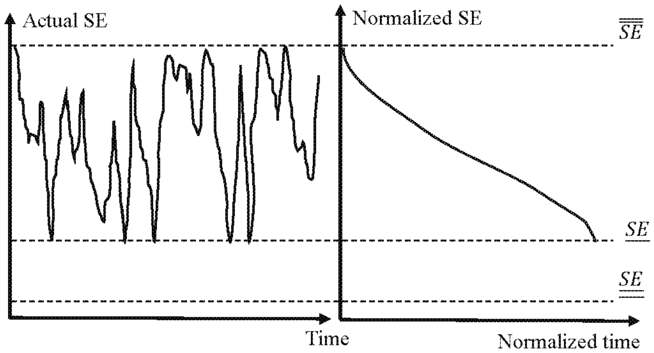

Fig. 4. Depth of discharge energy level ($\underline{SE}$) curve and the safe maximum, minimum energy levels ($\overline{\overline{SE}}, \underline{\underline{SE}}$).

Lifetime in quarters

The proposed formulation considers ESS lifetime in quarters to improve accuracy. The following constraint in (27) relates the number of quarters and the ESS cycle life. The equivalent cycle life considers the cycle life reduction due to fast charge.

$$NC + \Delta NC \leq \frac{\overline{NC}}{q} + \left(1 - B2_q\right) \cdot M \quad q \epsilon \{1,2,3..NQ\} \qquad (27a)$$

$$\sum_{q=1}^{NQ} B2_q = 1 \qquad (27b)$$

The complete formulation has an objective function in (1) to (9) and a set of constraints in (10) to (27). It can be solved used a mixed integer linear optimization solver.

IV. Case Studies

To validate the proposed merchant-owned ESS profit-maximization model, the formulation was implemented in the MATLAB® R2016a environment and solved using the mosek 7.0 solver. Based on Ontario 2016 hourly energy price data, several ESS were investigated using the model. The common economic data used for the study is given in Table I. Hourly Ontario Energy Prices (HOEP) in 2016 and reserve power price data were taken from [20] and [21]. This common data was used in all ESS case studies presented in other sections.

TABLE I
Input Data of Base Case

Price of annual frequency regulation contract (rFR)	156,000 CAD/MW
Price of annual black start service contract (rBS)	37,700 CAD/MW
Price of annual voltage regulation contract (rVR)	70,000 CAD/Mvar
Interest rate for the quarterly cost distributing factor (A)	0.011
Exchange rate USD/CAD	1.25

A. Base Case Study of a Li-ion Battery ESS

The assumed prices for the ESS given in Table II are within the price ranges mentioned in [22]. Other ESS technical parameters used for the analysis are also given in Table II. The basic results of the study are given in Table III.

TABLE II
Input Data for the Li-Ion Battery ESS

Inverter of ESS	
Rated active power ($\bar{P}$) (Charging, discharging)	20.0 MW
Maximum reactive power ($\overline{QVR}$)	19.0 MVAr
Minimum reactive power ($\underline{QVR}$)	-16.0 MVAr
Price (assumed)	250 USD/kW
Safe minimum SOC level ($\underline{SE}$)	0 MWh
Residual Energy capacity (SE_R)	23 MWh
No. of sections of cycle life vs DOD curve (NS)	5
Constants of NC vs SOC curve (KC_1, KD_1) first section	342.9, 300
Constants of NC vs SOC curve (KC_2, KD_2) second section	498.7, 280.5
Constants of NC vs SOC curve (KC_3, KD_3) third section	997.4,124. 7
Constants of NC vs SOC curve (KC_4, KD_4) fourth section	2,742.9, -857.1
Constants of NC vs SOC curve (KC_5, KD_5) fifth section	38,400, -27,600
Per hour Self-discharge rate (D)	0.002 MWh
Battery	
Rated active power (P)	20 MW
Rated energy ($\overline{SE}$)	32 MWh
Maximum number of cycles ($\overline{NC}$)	10,000
Price (assumed)	500 USD/kWh
Constant of inverter's capability curve (Kcc_1,Kcc_2)	0.5282, 1.2697
Efficiency of charging or discharging (EFF)	0.93
System parameters and constants	
Constants related to OMC cost (c_1, c_2, c_3)	0.02, 100, 20,000
Energy per 1 MW of frequency regulation power (KFR)	0.04 MWh/MW
Energy per 1 MW of reserve power (KRP)	0.2 MWh/MW
Maximum lifetime	10 years

TABLE III
Results of Base Case

Profit	
Annual profit	218,916 CAD
Power of each ancillary service	
Power of frequency regulation (PFR)	6.7 MW
Power of black start service (PBS)	2.0 MW
Power of voltage regulation (QVR)	19.0 MVAr
Power of energy arbitrage (PEA mean value)	-0.3 MW
Power of power reserve (PRP mean value)	7.7 MW
Lifetime	
Annual number of operating cycles (NC)	34.0
Used number of years	10

Pie charts in Fig. 5 show the annual revenues and costs from the ESS. Compared to investment cost, other costs are negligible. The ESS is predominantly used for frequency and voltage regulation.

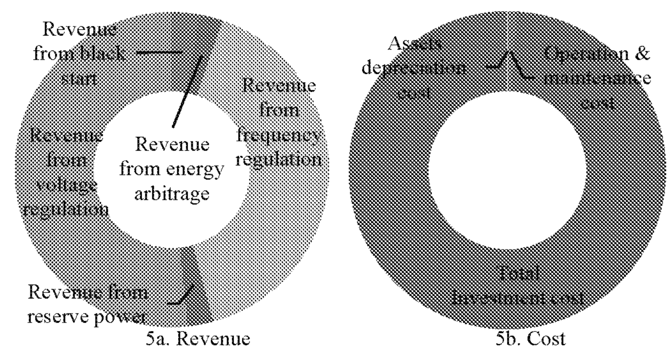

Fig. 5. Battery ESS – Base case revenues and costs

Fig. 6 and Fig. 7 show the real power commitments for ancillary services and energy arbitrage on a selected day

(23/02/2016). The commitments for reserve power and frequency regulation have both charging and discharging (negative and positive) values. The ESS is discharged on the 11^{th} and 21^{st} hours due to high market prices. It was charged on all other hours. The level of reactive power contract is 19 MVAr (not shown). Fig. 7 shows the ESS power positions on the capability curve in each hour. Note that hours 11 and 21 show positive PEA values in Fig. 6 and are located on the upper right-hand side of the capability chart in Fig. 7. In contrast, hours 1 to 10, 12 to 20 and 22 to 24 have negative PEA values in Fig. 6, which can be found on the upper left-hand side of the capability chart in Fig. 7.

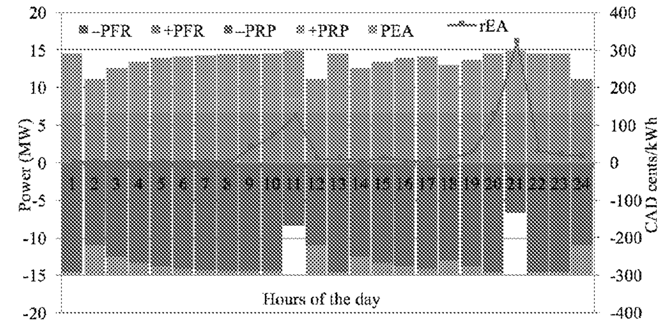

Fig. 6. Battery ESS real power of different ancillary services: energy arbitrage, frequency regulation and reserve power on (23/02/2016).

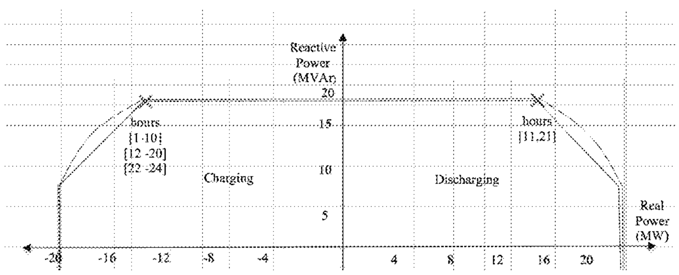

Fig. 7. Distribution of power of ancillary services in the 24-hour window on the capability curve.

To achieve the above power levels, the battery ESS needs to be fast charged during three hours. The level of fast charge (abuse, ΔP2) during these hours is shown in Fig. 8.

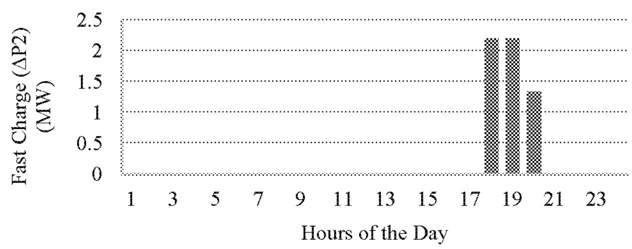

Fig. 8. Battery abuse (ΔP2) due to the fast charge on (06/09/2016).

B. *Sensitivity Study 1: Sensitivity to Investment Cost (IC)*

In general, the cost of energy storage is declining. A sensitivity analysis was conducted based on the total investment cost (IC) of EES to investigate the effect of the cost decrease on the profitability of ESS. Fig. 9 shows the effect of IC decrease on the ESS merchant's overall profit. Cases I, II, III, and IV refer to 10%, 20%, 30%, and 40 % reductions of investment cost respectively. It can be noted that with the reduction of investment cost, ESS generate higher overall profit compared to the base case.

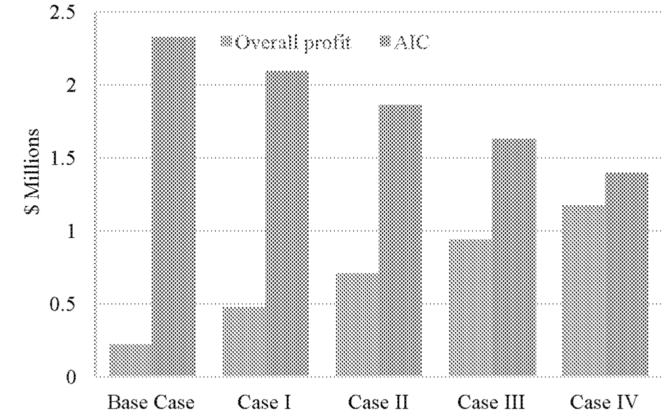

Fig. 9. Change of net profit with respect to change of investment cost

C. *Sensitivity Study 2: Sensitivity of Energy Price Forecast (rEA)*

In this sensitivity case, the effect of uncertainty of energy prices was investigated. The energy arbitrage profit of the ESS varies based on maximum and minimum (charge and discharge) electricity prices. This can be characterised using the price bandwidth (the difference between the maximum and minimum electricity prices). An analysis was conducted at different electricity price forecasts to investigate sensitivity to electricity market prices. The price forecasts were considered with both high and low-price bandwidths. Four price sensitivity cases (Cases V, VI, VII and VIII) were developed considering -20%, -40%, 20% and 40% electricity price bandwidths respectively. Prices of the base case were increased and decreased to create these cases. All these cases have the same price variation pattern and same mean price as the base case.

Fig. 10 shows the significant effect of the change of energy price on both the total revenue and the overall profit. In numerical terms, each 20% increase in energy price bandwidth could lead to a 10 % increase in the overall profit compared to the base case. However, reduction of the price bandwidth has limited impact on profit.

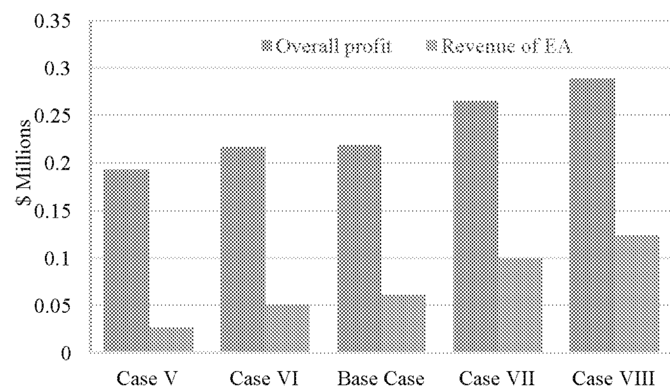

Fig. 10. Change of total revenue and net profit with respect to change of

energy price as % from base case price.

D. Sensitivity Study 3: Sensitivity to Energy Capacity of the EES

In this sensitivity case, the effect of changing energy capacity ($\overline{\overline{SE}}$) was investigated. Four sensitivity cases (Case IX-Case XII) were developed varying the energy capacity ($\overline{\overline{SE}}$), while maintaining the same power capacity ($\overline{PS}$). These cases represent 75%, 125%, 150%, and 175% of the base case ESS energy capacity. These energy capacities are Case IX – 15 MWh, Case X – 25 MWh, Case XI – 30 MWh and Case XII – 35 MWh. Fig. 11 shows the increase of the annual value of investment cost due to change of ESS energy capacity. On the other hand, it also shows the variation of net profit. It can be noted that high capacity ESS are less profitable compared to the smaller units.

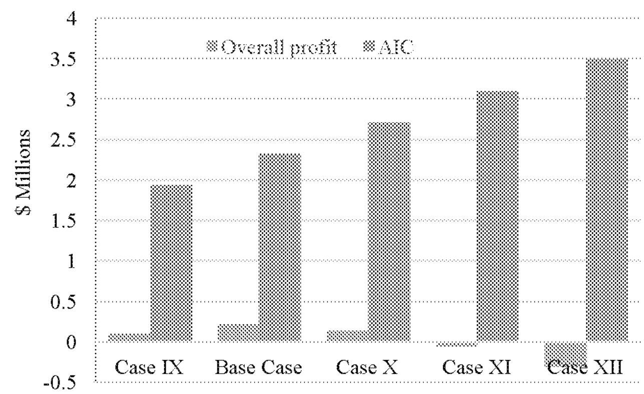

Fig. 11. Change of annual net profit value with respect to the change of total investment cost due to change of ESS energy capacity.

Fig. 12 shows the change of the revenue of each ancillary service due to the change of ESS energy capacity. It can be noted that the owner of the ESS could gain higher revenue from frequency regulation and voltage regulation than from energy arbitrage. From these sensitivity cases, it is clear that when the energy capacity increases, ESS energy capacity is mostly utilised for frequency regulation service.

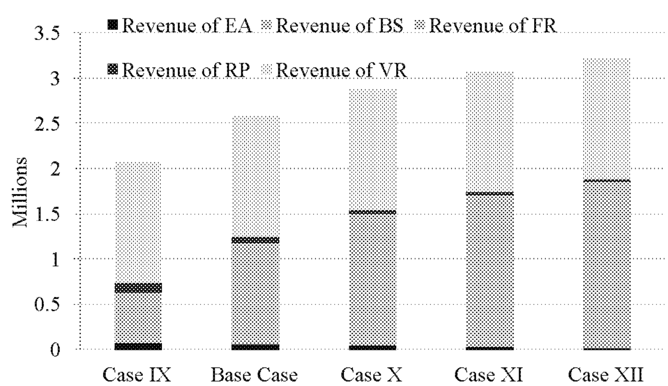

Fig. 12. Change of the revenues of each ancillary service with respect to the change of energy capacity of ESS.

E. Flywheel Energy Storage Case Study

The profitability of a merchant-owned flywheel energy storage was studied to verify the flexibility of the proposed model as a generic ESS planning model. For a flywheel ESS constraints (21) - (22) and (24) - (27) are not relevant. Other constraints and the objective function were solved. Relevant technical and cost parameters assumed for the flywheel ESS are presented in Table IV.

TABLE IV
INPUT DATA FOR THE FLYWHEEL ESS BASED ON [23]

Inverter of ESS	
Rated active power ($\overline{P}$) (Charging, discharging)	10.0 MW
Maximum reactive power ($\overline{QVR}$)	9.5 MVAr
Minimum reactive power ($\underline{QVR}$)	-9.5 MVAr
Price (assumed)	250 USD/kW
Constants of inverter's capability curve (Kcc_1, Kcc_2)	0.5282, 1.2697
Flywheel	
Rated active power (P)	10 MW
Rated energy ($\overline{SE}$)	2 MWh
Maximum number of cycles ($\overline{NC}$)	100,000
Price (assumed)	700 USD/kWh
Safe minimum SOC level ($\underline{SE}$)	0 MWh
Residual Energy capacity (SE_R)	2 MWh
Per hour Self-discharge rate (D)	0.0001 MWh/h
System parameters and constants	
Constants related to OMC cost (c_1, c_2, c_3)	0, 0, 10,000
Efficiency of charging or discharging (EFF)	0.93
Energy per 1 MW of frequency regulation power (KFR)	0.01 MWh/MW
Energy per 1 MW of reserve power (KRP)	0.2 MWh/MW
Maximum lifetime	20 years

The flywheel ESS is predominately used for providing frequency regulation support. Estimated annual profit of this ESS is CAD 1,529,506. It is also noted that the energy arbitrage does not generate any revenue and it is a cost. This means the flywheel uses grid energy to maintain the frequency regulation service. Fig. 13 shows the annual revenue and cost items of the considered flywheel ESS. Fig. 14 shows its operation on the 23rd February 2016. Even though energy arbitrage is a cost, this flywheel ESS tries to store and release energy as much as possible to reduce the cost. In hours 10,11, 20 and 21 it releases energy to the grid.

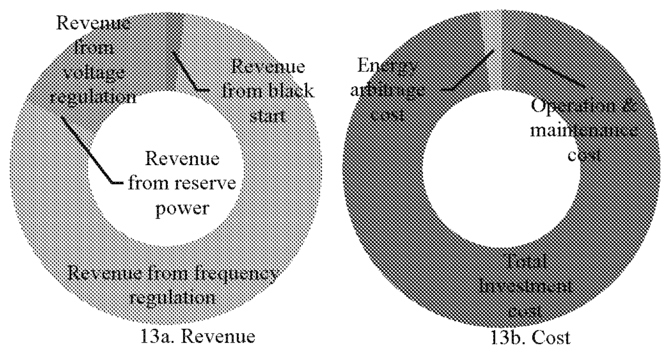

Fig. 13. Flywheel ESS revenue and cost

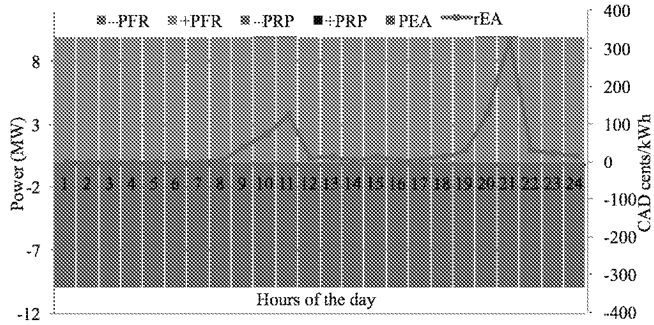

Fig. 14. Flywheel ESS real power of different ancillary services: energy arbitrage, frequency regulation and reserve power on (23/02/2016).

F. *Compressed Air Energy Storage Case Study*

The profitability of a merchant-owned compressed air ESS was also studied using the proposed model. Like the flywheel ESS case, constraints (21) - (22) and (24) - (27) are not relevant to this ESS. The assumed relevant techno-economic parameters for the compressed air ESS are given in Table V. These parameters are assumed based on values given in [23].

TABLE V
INPUT DATA FOR THE COMPRESSED AIR ESS BASED ON [23]

Inverter of ESS	
Rated active power ($\overline{P}$) (Charging, discharging)	50.0 MW
Maximum reactive power ($\overline{QVR}$)	45.0 MVAr
Minimum reactive power ($\underline{QVR}$)	-45.0 MVAr
Price (assumed)	1,210 USD/kW
Constants of inverter's capability curve (Kcc_1,Kcc_2)	0.5282, 1.2697
Flywheel	
Rated active power (P)	100 MW
Rated energy ($\overline{SE}$)	200 MWh
Maximum number of cycles ($\overline{NC}$)	100,000
Price (assumed)	151 USD/kWh
Safe minimum SOC level ($\underline{SE}$)	0 MWh
Residual Energy capacity (SE_R)	250 MWh
Per hour Self-discharge rate (D)	0.001 MWh/h
System parameters and constants	
Constants related to OMC cost (c_1, c_2, c_3)	0, 0.01, 10,000
Efficiency of charging or discharging (EFF)	0.7
Energy per 1 MW of frequency regulation power (KFR)	0.01 MWh/MW
Energy per 1 MW of reserve power (KRP)	0.2 MWh/MW
Maximum lifetime	20 years

Fig 15 and Fig. 16 show the results for the compressed air EES. The annual loss from the compressed air ESS is CAD 5,658,052. This size of compressed air ESS is not profitable under considered market price conditions.

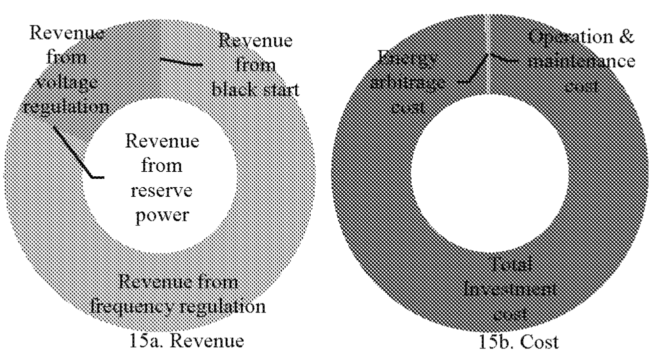

Fig. 15. Compressed Air ESS revenue and cost

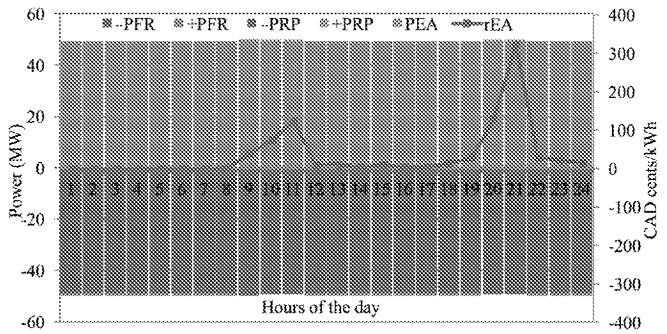

Fig. 16. Compressed Air ESS real power of different ancillary services: energy arbitrage, frequency regulation and reserve power on (23/02/2016).

Revenues and costs of these three ESS are shown in Fig. 17. Compressed Air ESS does not generate profit under the considered price regime. The best investment is the flywheel ESS. Even with a low investment, it generates higher profit than the battery ESS.

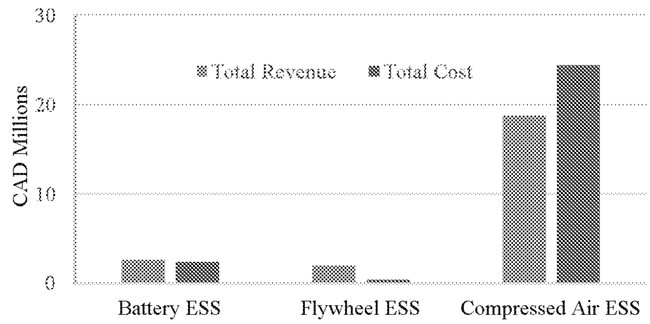

Fig. 17. Revenue and cost of different ESS

V. MAIN CONTRIBUTIONS

The proposed ESS scheduling model provides the following unique benefits from a merchant perspective:

1) The model can be used to assess the profitability of any type/size of ESS. The model accounts for all complex technical characteristics of different types of ESS.

2) The model also allows for analyzing and optimizing multiple ancillary services and energy arbitrage for the same ESS. It needs ESS technical parameters and price forecasts of each ancillary service to do so.

3) The model considers the ESS cycle life reduction based on the abuse and low depth of discharge operations. Hence the model optimizes the short-term operation decisions to achieve long-term economic benefits.

4) As shown in the ESS sizing sensitivity, the proposed model can be used as a planning tool to decide the most profitable power and energy capacity of the ESS.

5) The basis of the model is a linear formulation. Therefore, it can be used as a robust industrial planning tool for investment decisions.

VI. Conclusion

This paper proposes a new profit-maximizing formulation for ESS with multi ancillary services. The formulation considers five ancillary services: voltage regulation, frequency regulation, energy arbitrage, reverse power, and black start support. The model also considers all the expected costs associated with installation and operation, as well as depreciation of the asset.

The model is expected to help the ESS owners in decision making regarding optimal capacities for their ESS units. It also could help regarding their operational decisions and the best way to invest in ESS and gain the maximum profits. The model considers the abuse of ESS by fast charging and lifetime degradations in order to maximize both short-term operating decisions and long-term economic benefits for the ESS owners. The formulation is validated using Ontario's energy market data, and the results demonstrate that optimal sized battery and flywheel ESS can generate profits with current ESS prices. Frequency regulation, voltage regulation and black start support are the main revenue streams. From sensitivity studies, it is clear that the ESS can generate these profits even if the assumed parameters are changed considerably. The model is generic for any type/size of ESS and can be used to optimize the operation of any ESS technology such as flywheel and compressed air. It is proved that the proposed model could attract the attention of current and future ESS owners as well as the energy utilities which encourage incorporation of clean, renewable energy resources and energy storage.

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