Energy and Cost Minimization of Bidirectional Frequency Regulation Service by EV Following FERC Order 755

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***Abstract*—Increasing share of renewable energy sources in the electric sector, forces the system operators to include new resources for frequency regulations with fast ramping. Electric vehicles (EVs) with fast charging and short battery reaction time are becoming promising source for frequency regulations. Therefore, it is worthwhile to evaluate EV's abilities and associated cost to participate in the frequency regulation activity. In this paper, we first present a linear model of EV operating in charging/discharging mode and impact of battery degradation during these activities. We then define a cost function for EV operation and its minimization using linear programming. After calculating the optimal operating points of EV, a novel framework was developed to calculate optimal bidding components of EV, regulation capacity and energy cost function to participate in the regulation market. Simulation results show the efficiency of the developed linear model. Results also provide pathways for possible opportunities of revenue stream for the EV owner, by offering the regulation up/down services, without limiting the EV owners level of comfort.**

***Index Terms*—electric vehicle, frequency regulation, linear program, battery degradation.**

I. Introduction

Climate Change 2014 Synthesis Report suggests renewables will have to grow from their current 30% share to 80% of the power sector by 2050. In the longer term, the report states that fossil fuel power generation without carbon capture and storage technology would need to be phased out almost entirely by 2100 [1]. For wider adoption, intermittent nature of renewable sources needs to be overcome first.

Electric vehicles (EVs) with fast charger and short battery reaction time, make the vehicle-to-grid (V2G) services a promising source for ancillary services [2]. According to reference [3] The highest value ancillary service for EVs is frequency regulation. Frequency regulation is the use of on-line generation, storage, or load that is equipped with automatic generation control (AGC) and that can change output quickly (MW/min) to track the moment-to-moment fluctuations in customer loads and to correct for the unintended fluctuations in generation [4].

According to reference [5], as the penetration of renewable energy sources in the system increases, frequency regulation requirements as well as need for faster ramping resources will increase. This need has been recognized by Federal Energy Regulatory Commission (FERC). On October 20, 2011, FERC issued a final ruling establishing a two-component market-based compensation scheme (capacity payment and performance-based payment) for providing frequency regulation service [6]. Considering rapid response and large instantaneous power, EVs can provide a fast response when the mismatch between load and generation is large and happens in short duration [7].

Various demand response strategies for ancillary services by EVs have been reported in [8]-[11]. But so far no framework has been proposed which is easy to implement, scalable for large number of EVs, and satisfy FERC order 755. In this paper, we present a linear model representing EV operation which includes charging/discharging mode and battery degradation during these operations. Next, we then define a cost function for EV and minimize that using linear programming. After calculating the optimal operating points of EV for charging/discharging, we develop a framework to find the optimal bidding strategy to participate in the regulation market. Simulation results clearly show the high efficiency of the proposed framework and also generation of revenue stream for the EV owners participating in the regulation service activities. The rest of the paper is organized as follows: Section II presents calculation of the battery degradation during active power flow; Section III provides modeling of EV and model linearization; Calculation of optimal bidding components of the EV when participating in the regulation market is presented in Section IV; Section V discusses numerical results and is followed by Section VI the conclusions.

II. Battery Degradation Model

Let p_k denotes the active power flows of an EV charger at a given time instant k. The sign of p_k represents direction of the power flow. p_k^+ is for charging mode (from grid to EV) and p_k^- is for discharging mode (from EV to grid). To estimate the battery degradation, we have used the battery health model from the reference [12], and is shown below:

$$\begin{aligned}\dot{d}_k(I_k, V_k) = \beta_1 + \beta_2 \left\| I_k \right\| + \beta_3 V_k + \beta_4 \left\| I_k \right\|^2 \\ + \beta_5 V_k^2 + \beta_6 \left\| I_k \right\| V_k + \beta_7 V_k^3,\end{aligned} \tag{1}$$

where I_k is the current (charging when $I_k > 0$ and discharging when $I_k < 0$), V_k is the cell terminal voltage at a given time instant k, and d_k is the battery health in terms of energy capacity ($Amp \times hour \times sec^{-1}$). β_1 to β_7 are constant and their values are calculated from published results.

For the range of operation under consideration, between minimum and maximum SOC, the battery cell has a constant

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nominal voltage, V. Therefore, we can rewrite equation (1) in terms of p_k, as follows:

$$\dot{d}_k(p_k) = (\beta_1 V + \beta_3 V^2 + \beta_5 V^3 + \beta_7 V^4) + (\beta_2 + \beta_6) \|p_k\| + \frac{\beta_4}{V} \|p_k\|^2 \tag{2}$$

where $p_k = VI_k$. Therefore, The battery degradation at a given time interval k, in terms of capacity loss, could be expressed as below:

$$D_k(p_k) = \int_{t=0}^{t=\tau} \dot{d}_k(p_k) dt. \tag{3}$$

where τ, in seconds, is the time duration in which the degradation is being estimated.

The unit price of the battery cell capacity ($\$/Wh$), ϑ, is used to express the cost of capacity loss, C, at a given time interval k, as follows:

$$C(p_k) = \tau \vartheta D_k(p_k). \tag{4}$$

Above calculation is for a single cell of a battery. If we now assume a battery composed of n cells, the battery active power flow is divided to each cell equally, and SOC of each cell of the battery is of same value then the capacity loss of the whole battery can be calculated using the expression below:

$$C_k(p_k) = \tau \vartheta \left[(\beta_2 + \beta_6 V) \|p_k\| + \frac{\beta_4}{nV} \|p_k\|^2 \right]. \tag{5}$$

For example, consider a 3.6 kVA EV charger with a 16 kWh Lithium-Ion battery pack that is used in Mitsubishis i MiEV. This battery pack is composed of 22 cell modules connected in series at nominal voltage of 330 V. Each cell module is composed of 4 cells with nominal voltage of 3.7 V and capacity of 50 Ah. Energy unit price ($/kWh) for Lithium-Ion battery is assumed to be 500 $/kWh [13]. Using the values for β_1 to β_7 provided in reference [12], the battery degradation cost is calculated, for each time interval $\tau = 10$ minutes using the expression shown below.

$$C_k(p_k) = 0.0244 \|p_k\| + 0.0005 \|p_k\|^2. \tag{6}$$

Using values of V and β_1 to β_7 mentioned above, the conservative linear approximation of the battery degradation cost function will be:

$$C_k(p_k) \approx \tau \gamma \|p_k\|, \tag{7}$$

where $\gamma = \vartheta(\beta_2 + \beta_6 V + \frac{\beta_4}{nV} \bar{s})$. Notice that maximum active power flow is $\bar{s}$. The calculated γ value in this case is equal to 0.157 $/kWh.

III. Optimal Operation of EV

The first step is to calculate the set point for charging of the EV. To do so, we define an objective function first, using a model of the EV operation. To model the operation of an EV, we discretize EV parking time in T steps, each with duration τ. Let us assume the arrival time to be h_i and departure time is h_d. Therefore for a given τ, the number of time intervals when EV is parked, T, can be calculated as follows:

$$T = \frac{h_d - h_i}{\tau}.$$

Next, x_k defines the State of Charge (SOC) of the EV in time step k. Assuming initial SOC, x_i, desired SOC, x_d, and the capacity of the battery, ψ, we calculate the SOC of the EV in each time interval as follows:

$$\begin{cases} x_1 = x_i + \frac{\tau}{\psi} p_1, \\ x_2 = x_1 + \frac{\tau}{\psi} p_2, \\ \vdots \\ x_T = x_{T-1} + \frac{\tau}{\psi} p_T, \end{cases} \tag{8}$$

We then assume sets of non-negative prices for charging active power to be $\begin{bmatrix} \rho_1 & \rho_2 & \cdots & \rho_T \end{bmatrix}$ and for discharging active power to be $\begin{bmatrix} \nu_1 & \nu_2 & \cdots & \nu_T \end{bmatrix}$. The cost function f for operating the EV can then be defined by summing over time the costs associated with active power flows:

$$f = \sum_{k=1}^{T} f_c(p_k), \tag{9}$$

where

$$f_c(p_k) = \tau[(\frac{\rho_k}{\eta} + \gamma) p_k^+ + (\eta \nu_k - \gamma) p_k^-], \tag{10}$$

where p_k^+ and p_k^- represent charging and discharging operation, respectively. $p_k^+ = p_k$ if p_k is non-negative and zero otherwise, and $p_k^- = p_k$ if p_k is negative and zero otherwise. η is the efficiency of the battery, and γ is the degradation cost of the battery ($/kWh). If the EV is charging active power, $p_k > 0$, then the owner cost is at a rate of $(\frac{\rho_k}{\eta} + \gamma)$ per unit time. If the EV is discharging active power, $p_k < 0$, then the owner income is at a rate of $(\eta \nu_k - \gamma)$ per unit time.

Based on the cost function presented above, an optimization problem can be defined as follows:

$$\min_{p_k, x_k} \quad f, \tag{11}$$

subject to

$$\text{equations in (8), and } x_T = x_d, \tag{12}$$

$$-\overline{p} \le p_k \le \overline{p}, \tag{13}$$

$$\underline{x} \le x_k \le \overline{x}, \tag{14}$$

for all $k = 1, \cdots, T$. Constraint (12) guarantees that by the end of the parking time, the battery meets the desired SOC. Constraint (13) is related to the minimum and maximum active power flow. Notice that $\overline{p}$ is the maximum active power flow of the EV charger. The parameters $\underline{x}$ and $\overline{x}$ in (14) represent the minimum and maximum SOC of the EV battery, respectively.

Our aim is to approximate the above optimization problem with a linear program. To accomplish that we first redefine parameters, mentioned above, in matrix forms as follows:

$$p = \begin{bmatrix} p_1, & p_2, & \ldots, & p_T \end{bmatrix}^T, \ x = \begin{bmatrix} x_1, & x_2, & \ldots, & x_T \end{bmatrix}^T,$$

$$\rho = \begin{bmatrix} \rho_1, & \rho_2, & \ldots, & \rho_T \end{bmatrix}^T, \ \nu = \begin{bmatrix} \nu_1, & \nu_2, & \ldots, & \nu_T \end{bmatrix}^T,$$

$$e = \left[1,\ 0,\ \ldots,\ 0\right]^T_{T\times 1},$$

$$D:\ T\times T\ matrix\ with\ one\ on\ the\ first\ lower\ subdiagonal\ and\ zero\ elsewhere.$$

It should be noted that at each time step k, the price of charging active power is higher than the price of discharging active power. In other words $\frac{\rho_k}{\eta} + \gamma > \eta\nu_k - \gamma$.

We now rewrite the expression for f_c in a way so that it facilitates the formulation of a linear program.

$$f_c(p_k) = \max\{\tau(\frac{\rho_k}{\eta} + \gamma)p_k, \tau(\eta\nu_k - \gamma)p_k\}.$$

Now suppose c_k constitutes an upper bound for $f_c(p_k)$ at every k, that would imply

$$\tau(\frac{\rho}{\eta} + \gamma)\circ p \le c, \qquad \tau(\eta\nu - \gamma)\circ p \le c,$$

where $\circ$ denotes elementwise multiplication of vectors and

$$c = [c_1,\ c_2,\ \ldots,\ c_T]^T.$$

Thus the objective function f in equation (9) is upper bounded by $\mathbb{1}^T c$ which is linear with the optimization variables c. We now replace the objective function f in equation (11) with its upper bound, and since equation (11) is a minimization problem this upper bound will always be equal to f, i.e., the bound will not be conservative.

We replace the original optimization problem in equation (11) with the following linear program:

$$\underset{p,x,c}{\text{minimize}} \quad \mathbb{1}^T c, \tag{15}$$

subject to

$$x = x_i e + Dx + \frac{\tau}{\psi}p, \quad x_T = x_d, \tag{16}$$

$$-\overline{p} \le p \le \overline{p}, \tag{17}$$

$$\underline{x}\mathbb{1} \le x \le \overline{x}\mathbb{1}, \tag{18}$$

The solution of the optimization problem in equation 15 is then used to develop the optimal bidding strategy to participate in the regulation market.

IV. Bidding Strategy

An EV can participate in regulation up service by decreasing its scheduled charging demand or increasing its discharging power. The regulation down service can also be provided by the EV by increasing its charging demand or decreasing its discharging power. Assuming p_k^* to be the optimal operating point of EV in time step k, Fig. 1 demonstrates the frequency regulation service that needs to be provided by the EV to fulfil the service requirement.

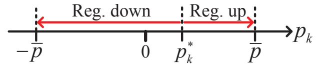

Fig. 1. Frequency regulation service from EV in time step k.

The bid from the EV must contain the offered capacity of power (kW) for the regulation service along with an energy cost function [6]. Therefore we next develop a framework to calculate the optimal bidding components for the EV.

A. Capacity Allocation

We define two parameters, $u_k^\uparrow$ and $u_k^\downarrow$, representing the offered regulation up and down capacity from the EV in time step k, respectively. As can be seen from Fig. 1, providing frequency regulation service results in deviation from the scheduled charging/discharging power during the time interval. So, to meet the desired SOC, charging/discharging activity must be rescheduled in the receding horizon (time steps from k+1 to T). Therefore the maximum amount of the capacity power for frequency regulation services that can be offered by the EV at time step k, will depend on whether the battery can reach its desired SOC in the receding horizon.

To calculate the capacity power that can be offered by the EV for regulation service, we first define the maximum reschedulable capacity power in the receding horizon. For this purpose we use $\overline{u_k^\uparrow}$ and $\overline{u_k^\downarrow}$ representing the maximum and minimum available reschedulable capacity power for regulation up and regulation down service, respectively. These two parameters are calculated as follows:

$$\overline{u_k^\uparrow} = \sum_{t=k+1}^{T} (\overline{p} + p_t^*), \tag{19}$$

$$\overline{u_k^\downarrow} = \sum_{t=k+1}^{T} (\overline{p} - p_t^*). \tag{20}$$

The capacity power that can be offered for regulation up and down services is then calculated as shown below:

$$u_k^\uparrow = \begin{cases} \overline{p} + p_k^*, & if\ \overline{p} + p_k^* \le \overline{u_k^\uparrow}; \\ \overline{u_k^\uparrow}, & if\ \overline{p} + p_k^* > \overline{u_k^\uparrow}; \end{cases} \tag{21}$$

$$u_k^\downarrow = \begin{cases} \overline{p} - p_k^*, & if\ \overline{p} - p_k^* \le \overline{u_k^\downarrow}; \\ \overline{u_k^\downarrow}, & if\ \overline{p} - p_k^*, > \overline{u_k^\downarrow}. \end{cases} \tag{22}$$

B. Energy Cost Function

As discussed above, to meet the desired SOC of the EV, the charging/discharging activity must be rescheduled in the receding horizon. Since the scheduled operating points are optimal, any deviation from optimal charging/discharging will increase the operating cost of the EV. This additional cost imposed on the EV is defined as the energy cost function for frequency regulation services.

We assume that non-negative parameters $\Delta p_k^\uparrow$ and $\Delta p_k^\downarrow$ represent the deviation from scheduled charging/discharging power of the EV in time step k for regulation up and regulation down, respectively. We also assume that the time step rc in the receding horizon ($rc \in [k+1, T]$) is assigned for rescheduling the charging/discharging activity. Table I summarizes the change in operating points of the EV in time interval k (for providing regulation services) and the time interval rc of the receding horizon (for rescheduling the charging/discharging activity). Up-arrow and down-arrow in the table represent increasing and decreasing action, respectively. We have defined four cases for possible changes in operating points. For example, for regulation up service in Case I in which the EV is charging during both time intervals k and rc. Any decrease in charging power during time interval k would cause an increase in charging power during time interval rc as indicated in the forth column. This procedure would impact the operating cost by decreasing charging cost at time interval k and increase charging cost at time interval rc.

TABLE I
CHANGE IN OPERATING POINTS OF EV DUE TO REGULATION SERVICES.

	Mode of operation at time interval		Change in operating points caused by services	
	k	rc	Reg. up	Reg. down
Case I	Charg.	Charg.	$\downarrow$ charg. at k $\uparrow$ charg. at rc	$\uparrow$ chrg. at k $\downarrow$ chrg. at rc
Case II	Disch.	Charg.	$\uparrow$ disch. at k $\uparrow$ chrg. at rc	$\downarrow$ disch. at k $\downarrow$ chrg. at rc
Case III	Charg.	Disch.	$\downarrow$ chrg. at k $\downarrow$ disch. at rc	$\uparrow$ chrg. at k $\uparrow$ disch. at rc
Case IV	Disch.	Disch.	$\uparrow$ disch. at k $\downarrow$ disch. at rc	$\downarrow$ disch. at k $\downarrow$ disch. at rc

The change in the operating cost of the EV due to frequency regulation up and down services can be calculated as follows:

$$\Delta f = \begin{cases} \Delta p_k^{\uparrow}\tau(-\frac{\rho_k}{\eta} + \frac{\rho_{rc}}{\eta}), & \text{for Case I;} \\ \Delta p_k^{\uparrow}\tau(\gamma + \frac{\rho_{rc}}{\eta} + \gamma), & \text{for Case II;} \\ \Delta p_k^{\uparrow}\tau(-\frac{\rho_k}{\eta} - \gamma + \eta\nu_k - \gamma), & \text{for Case III;} \\ \Delta p_k^{\uparrow}\tau(\eta\nu_{rc}), & \text{for Case IV;} \end{cases} \tag{23}$$

$$\Delta f = \begin{cases} \Delta p_k^{\downarrow}\tau(\frac{\rho_k}{\eta} - \frac{\rho_{rc}}{\eta}), & \text{for Case I;} \\ \Delta p_k^{\downarrow}\tau(\eta\nu_k - \gamma - \frac{\rho_{rc}}{\eta} - \gamma), & \text{for Case II;} \\ \Delta p_k^{\downarrow}\tau(\frac{\rho_k}{\eta} + \gamma + \gamma), & \text{for Case III;} \\ \Delta p_k^{\downarrow}\tau(\eta\nu_k - \gamma + \eta\nu_{rc} - \gamma), & \text{for Case IV;} \end{cases} \tag{24}$$

Marginal cost of providing regulation services, per unit time, can then be calculated as follows:

$$MC_k^{\uparrow} = \frac{\Delta f}{\Delta p_k^{\uparrow}} = \begin{cases} -\frac{\rho_k}{\eta} + \frac{\rho_{rc}}{\eta}, & \text{for Case I;} \\ \frac{\rho_{rc}}{\eta} + 2\gamma, & \text{for Case II;} \\ -\frac{\rho_k}{\eta} + \eta\nu_k - 2\gamma, & \text{for Case III;} \\ \eta\nu_{rc}, & \text{for Case IV;} \end{cases} \tag{25}$$

$$MC_k^{\downarrow} = \frac{\Delta f}{\Delta p_k^{\downarrow}} = \begin{cases} \frac{\rho_k}{\eta} - \frac{\rho_{rc}}{\eta}, & \text{for Case I;} \\ \eta\nu_k - \frac{\rho_{rc}}{\eta} - 2\gamma, & \text{for Case II;} \\ \frac{\rho_k}{\eta} + 2\gamma, & \text{for Case III;} \\ \eta\nu_k + \eta\nu_{rc} - 2\gamma, & \text{for Case IV;} \end{cases} \tag{26}$$

Time step rc in the receding horizon should be selected to minimize the marginal cost of the service. This means that the additional cost for rescheduling the charging/discharging activity in the receding horizon needs to be minimized. The energy cost function can then be calculated, as the summation of marginal costs during time interval k and time interval rc.

V. RESULTS AND DISCUSSION

A 3.6 kVA EV charger has been used for simulations. For the battery pack, we have used 16 kWh battery that is typically used in the Mitsubishi's i MiEV. The degradation factor for this battery was calculated in Section II and is equal to $\gamma = 0.157$ \$/kWh, for time intervals of 10 minutes. The minimum and maximum SOC of the EV are assumed to be 20% and 90% respectively. We also assume that the EV is connected from 9 a.m. to 5 p.m. with initial SOC of 40% and desired SOC of 90%. We have assumed 40% for initial SOC just to indicate that EVs can be connected with initial SOC other than minimum value.

For the price of electricity, we have used a week day (November 12, 2014) price published by New York Independant System Operator (NYISO) for Central zone. Since the market period for regulation services in the NYISO territory is 10 minutes, the value of τ is 0.167 hour which is consistent with NYISO regulation market. In the absence of any market for discharging power by EVs, we have assumed the price of discharged power to the grid to be 80% of the price of the electricity.

Fig. 2 shows the simulation result showing the charging demand of the EV, along with available capacity for regulation up and regulation down services. As can be seen, due to high battery degradation cost compare to income from power discharge, no discharging activity has been scheduled for the EV. Charging tasks has been scheduled during periods with lower electricity prices. However, during all those periods when the active power flows are zero, the EV can offer 3.6 kW capacity power for regulation up and 3.6 kW for regulation down service for the scheduled 10-minute time period. This fact clearly demonstrates the available opportunity for the EV to participate in frequency regulation activities. Also during those time intervals, in which the active power flows are non-zero, the EV has the capacity to offer regulation services. For example in time intervals when the charging power is equal to 3.6 kW, the EV can offer up to 7.2 kW capacity power for regulation up service (3.6 kW by decreasing the charging demand and another 3.6 kW by discharging power).

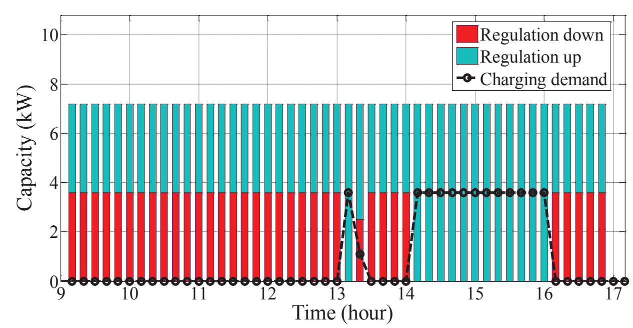

Fig. 2. Optimal charging demand and offered regulation capacity of the EV.

We can observe that during peak periods with high electricity price, the EV can offer up to its full charging and discharging capacity for regulation down or regulation up services, respectively. For system operator, these services during peak periods would be very useful.

Fig. 3 shows the energy cost function of regulation up and regulation down services at hour 10 a.m. (for example) when the charging power is zero. The price of regulation down service during this time interval is very small because rescheduling of charging activity up to 3.6 kW can be done in the receding horizon with small additional cost. However the price of regulation up service is high because of higher battery discharging price which includes battery degradation cost.

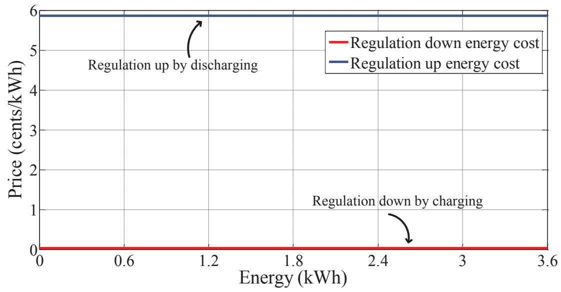

Fig. 3. Energy cost function for regulation up/down services at 10 a.m.

Fig. 4 shows the energy cost function of the services at hour 1:10 p.m., when the charging power is 1.1 kW. The price for regulation down service is zero because the deviation from the optimal charging can be rescheduled in the receding horizon without additional cost. For the same reason, the price of regulation up service is zero up to 1.1 kWh but, because of high discharging cost, the price jumps to 5.87 cents/kWh for regulation up service above and beyond 1.1 kWh.

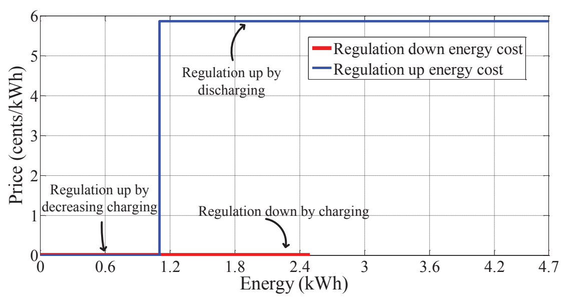

Fig. 4. Energy cost function for regulation up/down services at 1:10 p.m.

Fig. 5 presents the energy cost function for regulation up service at hour 4 p.m., when the charging power is set to its maximum value 3.6 kW. Therefore it is obvious that the regulation down capacity power is zero at this time. The price for regulation down service is 0.1981 cents/kWh up to 3.6 kWh. This service is provided by decreasing the amount of charging power. However, the price jumps to 6.053 cents/kWh for regulation up service above and beyond 3.6 kWh when the service is provided by discharging power from the EV.

VI. Conclusion

Integration of renewable resources into the system, requires fast ramping sources for frequency regulation. This need has been highlighted in FERC order 755. EVs, with fast charging and short battery reaction time, can participate efficiently as a frequency regulation resource. In this paper, we have presented a linear model of the EV which includes charging/discharging modes of operation and the battery degradation factor. We have defined a cost function for EV operation and then developed a framework to simultaneously minimize the operating cost of

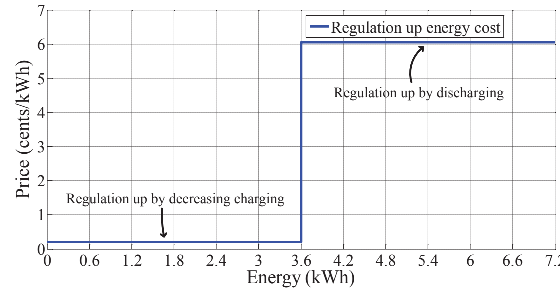

Fig. 5. Energy cost function for regulation up services at 4 p.m.

the EV and calculate optimal bidding strategy to participate in the frequency regulation market. To demonstrate the functionality of the developed framework, we have presented three example conditions that include no active power flow, some active power flow, and maximum active power flow condition. Simulation results show the high efficiency of the developed framework. Results also indicate the potential revenue stream for the EV owner without lowering the level of comfort. The linear nature of the model clearly imply its easier scalability potential.

References

[1] IPCC Fifth Assessment Synthesis Report, *Climate Change 2014 Synthesis Report*, November, 2014.

[2] M. Nikkhah Mojdehi and P. Ghosh, “Modeling and revenue estimation of EV as reactive power service provider,” Proc. of *IEEE PES General Meeting*, pp. 1–5, 2014.

[3] W. Kempton, V. Udo, K. Huber, K. Komara, S. Letendre, S. Baker, D. Brunner, and N. Pearre, “A test of vehicle-to-grid (V2G) for energy storage and frequency regulation in the PJM system,” University of Delaware, Newark, Report, 2008.

[4] B. J. Kirby, “Frequency regulation basics and trends,” Oak Ridge National Laboratory, Technical Report, 2004.

[5] A. D. Papalexopoulos and P. E. Andrianesis, “Performance-based pricing of frequency regulation in electricity markets,” *IEEE Transactions on Power Systems*, vol. 29, no. 1, 2014.

[6] Federal Energy Regulatory Commission. Order No. 755. Frequency Regulation Compensation in the Organized Wholesale Power Markets, Oct. 20, 2011. [online]. Available: http://www.ferc.gov.

[7] J. Zhong, L. He, C. Li, Y. Cao, J. Wang, B. Fang, L. Zeng, and G. Xiao, “Coordinated control for large-scale EV charging facilities and energy storage devices participating in frequency regulation,” *Applied Energy*, vol. 123, pp. 253–262, 2014.

[8] E. Sortomme and M. A. El-Sharkawi, “Optimal charging strategies for unidirectional vehicle-to-grid,“ *IEEE Transactions on Smart Grid*, vol. 2, no. 1, pp. 131–138, 2011.

[9] S. Shao, M. Pipattanasomporn, and S. Rahman, “Demand response as a load shaping too in an intelligent grid with electric vehicles,” *IEEE Transactions on Smart Grid*, vol. 2, no. 4, pp. 624–631, 2011.

[10] S. Shao, M. Pipattanasomporn, and S. Rahman, “Grid integration of electric vehicles and demand response with customer choice,” *IEEE Transactions on Smart Grid*, vol. 3, no. 1, pp. 543–549, 2012.

[11] J. Soares, H. Morais, T. Sousa, Z. Vale, and P. Faria, “Day-ahead resource scheduling including demand response for electric vehicles,” *IEEE Transactions on Smart Grid*, vol. 4, no. 1, pp. 596–605, 2013.

[12] J. C. Forman, “Minimally Invasive Characterization of Lithium Phosphate Battery Electrochemical and Health Models using Fisher Information and Optimal Experimental Design,” Ph.D. dissertation, Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI, 2012.

[13] R. Carnegie, D. Gotham, D. Nderitu, and P. V. Preckel, “Utility scale energy storage systems: benefits, applications, and technologies,“ *State Utility Forecasting Group*, 2013. Available: http://www.purdue.edu/discoverypark/energy/assets/pdfs/SUFG/publications/SUFG%20Energy%20Storage%20Report.pdf.