J Electr Eng Technol.2015; 10(3): 1335-1341
http://dx.doi.org/10.5370/JEET.2015.10.3.1335

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Decentralized Vehicle-to-Grid Design for Frequency Regulation within Price-based Operation

Seung Wan Kim*, Young Gyu Jin†, Yong Hyun Song* and Yong Tae Yoon*

Abstract – The utilization of electric vehicles has been suggested to support the frequency regulation of power system. Assuming that an intermediate aggregator exists, this study suggests a decentralized vehicle-to-grid operation scheme in which each vehicle-to-grid aggregator can behave independently of the power system operator. To implement this type of decentralized operation, this study adopts a price-based operation that has been proposed by many researches as an alternative operation scheme for the power system. In this environment, each vehicle-to-grid aggregator can determine its participation in vehicle-to-grid service in consideration of its residual energy of aggregated system and real-time market price. Consequently, the main purpose of this study is to verify whether or not the vehicle-to-grid power can effectively support the current frequency regulation function within the price-based operation scheme. Specifically, a frequency regulation method is proposed based on the real-time price signal, and a feedback controller for battery management is designed for decentralized vehicle-to-grid operation.

Keywords: Decentralized operation, Frequency regulation, Real-time price, Vehicle-to-grid

1. Introduction

Recent studies on frequency regulation using battery energy storage systems have received considerable attention [1-4] because a battery is a suitable component for reducing frequency deviation given its fast response speed [3, 4]. However, a battery that only regulates frequency is not a cost-effective resource because of its heavy investment cost. Hence, the use of the idle energy in the small batteries of many parked electric vehicles (EVs) can be considered an alternative. The idea of utilizing EVs to support power system operation is called vehicle-to-grid (V2G) [5, 6]. Much recent research has focused on this concept.

A V2G control structure was proposed in [7]. This structure applies the inverter-based droop method to each EV without the help of a central entity. In contrast to [7], an intermediate aggregator is introduced in [8, 9] to control many EVs. In these studies, the aggregated battery system is examined and the optimal charging strategy is derived based on the direct regulation signal from the power system operator.

The current study not only assumes the existence of an intermediate aggregator as in [8, 9] but also suggests a decentralized V2G operation scheme in which each V2G aggregator can behave independently of a power system operator. To implement this type of decentralized operation, this study adopts a price-based operation (PBO) that is proposed by many researches [10-12] as an alternative operation scheme for the power system. Within the PBO scheme, a system operator indirectly controls the power system by continuously publishing the real-time price to price-responsive participants [13]. In this environment, each V2G aggregator can determine its participation in V2G service in consideration of its residual energy of aggregated system and real-time market price. The V2G aggregator is labeled as the V2G service entity (V2GSE) in this study. Consequently, the main purpose of this research is to verify whether or not V2G power can effectively support the current frequency regulation function within the PBO scheme. Specifically, a frequency regulation method is proposed based on the real-time price signal for the V2GSE, and a feedback controller for battery management is designed for decentralized V2G operation. Although the basic concept of this study was introduced in [14], its description the structure of the battery management controller is insufficient. Therefore, the current research details the specific structure of the battery management controller with two feedback loops, which consist of an inner feedback loop for managing the state of charge (SOC) and an outer feedback loop for generating the price.

The remainder of this paper is organized as follows. As a preliminary section, Section 2 describes a general V2G operation scheme and an aggregated battery model. Section 3 proposes a V2G control scheme based on the real-time price signal. It also presents a battery management controller design for decentralized V2G operation. Section 4 depicts the verification of the effectiveness of the proposed scheme by simulation with the IEEE 39 bus

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† Corresponding Author: Wind energy Gird-Adaptive Technology Research Center, Chonbuk National University, Korea. (ygjin93@ snu.ac.kr)

* Dept. of Electrical and Computer Engineering, Seoul National University, Korea. ({pc9873, flustra, ytyoon}@ snu.ac.kr)

Received: November 6, 2014; Accepted: January 11, 2015

network. Section 5 presents the concluding remarks.

2. Preliminaries for the Decentralized V2G

2.1 Structure of the V2G operation

The V2GSE not only meets the electricity demand of each EV but also supplies aggregated power from EVs to the power system. The V2GSE can be categorized into two types depending on the location of the charging stations. One type is an entity that targets EVs in the parking lot of each office or residential building. In the other type, such transactions are conducted within the charging stations that sell the charging service in the downtown. These stations are similar to gas stations. Nonetheless, the second V2GSE type is unsuitable for frequency regulation because the staying time of the EVs in the downtown charging station is not long enough to provide stored energy to the power system in a timely manner. Therefore, the first V2GSE type in the parking lot is considered in the current study. Multiple V2GSEs of such a type are presumably available to support the frequency regulation function within a competitive V2G service market. The entire V2G operation scheme through V2GSEs is represented in Fig. 1.

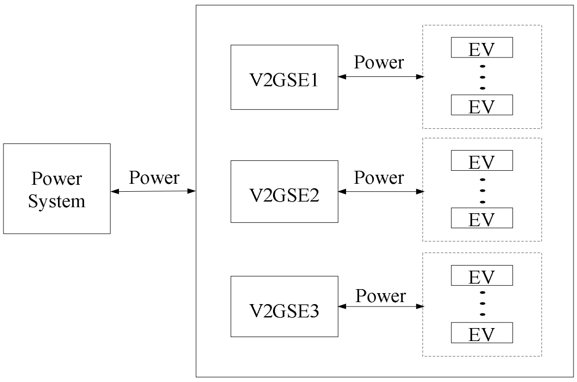

Fig. 1. V2G operation structure with V2GSEs.

2.2 Aggregated battery system

Each V2GSE has a virtual large battery that is composed of many small batteries that belong to the EVs in the charging station. The V2GSE always provides a charging service to the EVs in the charging station. It can also obtain power from the EVs; thus it can supply V2G power to the main power system when necessary. The specific V2GSE charging/discharging control depends on the charging requests from EVs and the market prices of electricity. In this study, the virtual aggregated battery system of V2GSE is modeled as a Thevenin-based model to represent the control scheme simply [15]. This aggregated model has an ideal voltage source in series with an internal resistance R_{series} and a parallel RC circuit composed of R_t and C_t.

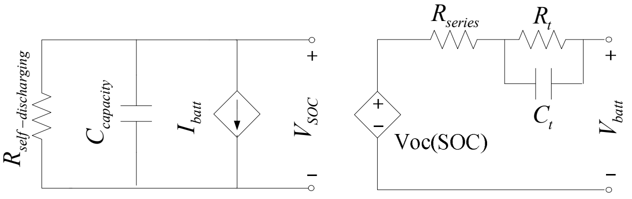

Fig. 2. Aggregated battery model.

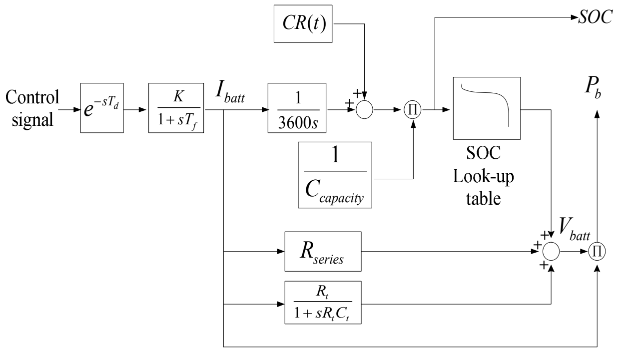

Fig. 3. Control block diagram of aggregated battery model.

The parallel RC network represents battery response to transient load events. This model also has a Runtime-based function, which consists of a parallel RC circuit ($R_{self\text{-}discharging}$ and $C_{capacity}$) and a dependent current source (I_{batt}). This substructure estimates battery SOC through the voltage (V_{SOC}) running throughout the current source. The overall structure of the aggregated battery model is illustrated in Fig. 2. This model in Fig. 2 can be represented by the control block diagram exhibited in Fig. 3.

A control signal is delayed by the value of T_d, which includes battery system activation time and communication delay. The signal then passes through the first-order filter to eliminate high frequency signals. The signal is then converted into an electric current signal, denoted as I_{batt}. The residual battery energy is estimated by the "coulomb counting" method [16]. The residual energy of the *i*-th electric vehicle is denoted as RE_{EV_i}. Then, the residual energy of the aggregated battery system, denoted as $CR(t)$, can be described as

$$CR(t)=\sum_{i=1}^{N(t)} RE_{EV_i}\ , \tag{1}$$

where $N(t)$ is the number of electric vehicles that participate at a certain time *t*. The full capacity of the aggregated battery is calculated by summing up each capacity C_{EV_i} as follows

$$C_{capacity}(t)=\sum_{i=1}^{N(t)} C_{EV_i}\ . \tag{2}$$

Relative SOC is then normalized to the battery capacity $C_{capacity}$ as follows

$$SOC(\%) = \frac{CR(t)}{C_{capacity}(t)} \times 100 . \quad (3)$$

V2GSE measures the current residual energy of the aggregated battery using (1) and calculates SOC by dividing its result by that of (2). The SOC of an aggregated battery at a certain time can be computed as presented in Fig. 4. Eq. (3) shows that the value of the aggregated SOC ranges between 0% and 100%. However, the SOC of each EV should be limited within the range of 20% to 95% to benefit battery life. The output voltage of the battery is determined through the SOC lookup table in Fig. 5, which defines a nonlinear relationship between the output voltage V_{batt} and battery SOC.

The current study scales the practical experimental result in [15] to fit the assumed battery specification. Then, a specific relationship between voltage and SOC can be expressed as

$$\begin{aligned} V_{OC}(SOC) = -57.736e^{-35SOC} + 206.36 + 12.0376 \cdot SOC \\ -6.5968 \cdot SOC^2 + 17.9256 \cdot SOC^3 . \end{aligned} \quad (4)$$

The voltage that corresponds to an SOC value can be determined by employing the graph in Fig. 5 as a look-up table. The terminal discharging voltage consists of $V_{OC}(SOC)$, the series resistance voltage drop V_{series}, and the voltage transient response $V_{transient}$.

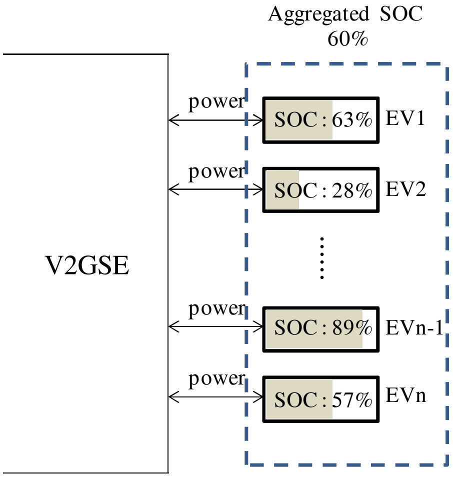

Fig. 4. Example of SOC calculation in the aggregated battery system.

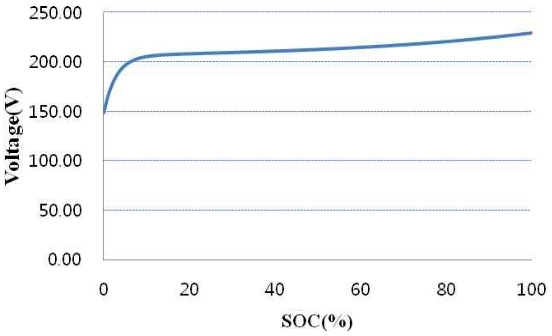

Fig. 5. Exemplary nonlinear relationship between output voltage and battery SOC.

3. Employment of the Decentralized V2G for Frequency Regulation

3.1 Price-based V2G operation scheme

A power mismatch is inherent in the power system because of demand fluctuation. The accumulated power mismatch over time is called an energy imbalance [17]. The energy imbalance is linearly related to the deviation in frequency from its nominal value (e.g., 60 Hz). The deviation is measured by the power system operator and is converted further into a change in real-time price signal through the real-time price generating process within the PBO scheme. The signal instructs price-responsive participants to manipulate their output so that the deviated frequency can revert to the nominal frequency. However, the frequency regulation performance of the current scheme is constrained by the ramp rate and reserve capacity limits of conventional generators. In this situation, V2GSE can support the frequency regulation with the aggregated battery system.

In contrast to the approach in other previous researches [8, 9] using the direct control of the central system operator, the virtual aggregated battery system in Fig. 3 is modified in this study to be capable of responding to real-time prices by adding a time differential block in front of the battery system. In the proposed model, the battery system takes as an input the derivative of the difference between real-time price and its own threshold price. The input signal represents the degree of energy imbalance in the power system. This method enables the battery system to adjust its charging / discharging power from/to the power system in consideration of the energy imbalance or the frequency deviation in the power system. Power is either charged / discharged by the battery management controller in front of the battery system depending on its SOC value. Each V2GSE decides independently on the basis of its own SOC. Thus, this process is decentralized and does not receive a command from a central operator.

3.2 Battery management controller of V2GSE

Each V2GSE provides a charging service to EVs in its charging stations. It also supplies energy to the power system when the real-time price becomes higher than its own threshold price. In this case, V2GSE sells the power to the grid until the price reaches the threshold. Conversely, V2GSE purchases power from the grid and charges the aggregated battery if the real-time price is lower than the threshold price.

Meanwhile, the price fluctuates in accordance with the energy imbalance in the power system [12, 13]. Therefore, V2GSE cannot appropriately manage the SOC for the time-varying price input given a fixed threshold price. Each V2GSE determines the quantity of charging power independently along with the residual energy in its battery and the charging demand from EVs. This determination is represented through the threshold price λ_{Th}. For example, if one V2GSE does not have sufficient SOC to provide charging services to an expected number of EVs at a certain time, then it increases its usual threshold price. To handle the continuous changes in both the charging demand of EVs and the real-time prices issued by the power system operator, V2GSE also adjusts its threshold price in real time based on a pre-scheduled SOC (SOC_{SCH}). When the SOC level drops below the scheduled one, the discharging power should be diminished gradually by increasing the threshold price. In other words, V2GSE controls the deviation of its SOC value from the scheduled one that is close to zero.

The feedback process is described as in Fig. 6. The battery management controller $G(s)$ generates the appropriate threshold price λ_{Th} based on the difference between SOC and the pre-scheduled SOC. Then, the threshold price λ_{Th} is subtracted from real-time price λ. This difference signal goes into the aggregated battery system $H(s)$. This aggregated battery system generates an SOC output and is fed into the battery management controller through a feedback loop. As an implementation of $G(s)$, the various forms of a controller may be applied. As an implementation of $G(s)$, various forms of a controller is possibly applied, whereas a typical PID controller is selected in this study. The optimal operation strategy of the battery management controller can be determined by a dynamic programming process on the basis of the fluctuation of historical frequency fluctuation and on the probability distribution of EV charging demands.

The dynamic programming approach to the inventory problem [18] can be applied to determine the optimal operation strategy of the battery management controller. The simplest part of the optimal solution can be described according to the result because the optimal operation strategy maintains its scheduled value for certain time duration regardless of demand uncertainty. The complete description of the optimal solution is very complex and is beyond the scope of this study; thus, the fixed value of the scheduled SOC value is applied as a given parameter in the short duration of this study.

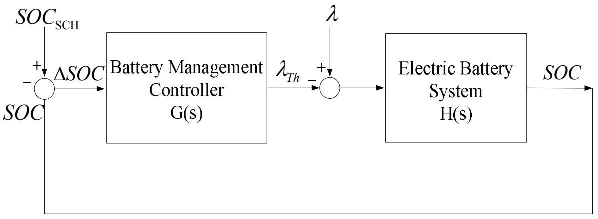

Fig. 6. Control block diagram of the electric battery system and battery management controller.

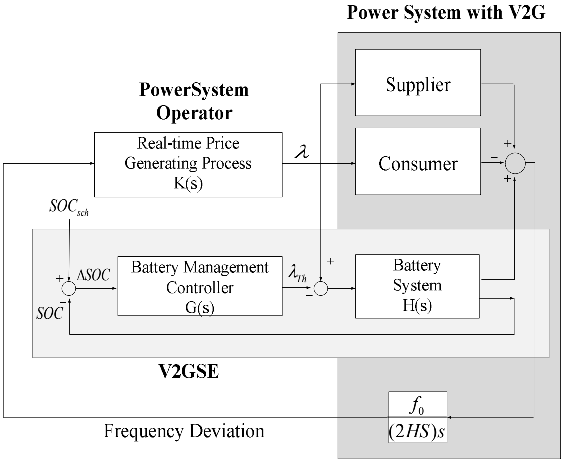

Fig. 7. Control structure of the proposed V2G scheme.

The entire control structure of the proposed V2G scheme is described in Fig. 7. This structure is applied to each V2GSE as in Fig. 1. However, the specific control methods can differ from one another. Thus, the structure of the proposed scheme can be suitable for a decentralized V2G operation.

4. Simulation and Verification

4.1 Configuration

In the simulations, the *i*-th supplier is presumably based on market dynamics equations derived from [19]. This supplier is represented as

$$\tau_{g,i}\dot{P}_{g,i} = \lambda - (b_{g,i} + c_{g,i}P_{g,i}),\ \ i = 1,\cdots,m \tag{5}$$

where $P_{g,i}$ is the generated quantity; $b_{g,i} + c_{g,i}P_{g,i}$ is the marginal cost; $\tau_{g,i}$ is the time constant; and m is the number of suppliers. Under the assumption of the IEEE 39 bus network, the values for these parameters are obtained from [13] and listed in Table 1.

Table 1. Parameters for the dynamic behaviors of 10 suppliers in the IEEE 39 bus network.

Bus Number	Participant Dynamics Parameters		
	τ_g	c_g	b_g
30	35/60	0.8	30.00
31	35/60	0.7	35.99
32	25/60	0.7	35.45
33	30/60	0.8	34.94
34	25/60	0.8	35.94
35	30/60	0.8	34.80
36	30/60	1.0	34.40
37	30/60	0.8	35.68
38	30/60	0.8	33.36
39	35/60	0.6	34.00

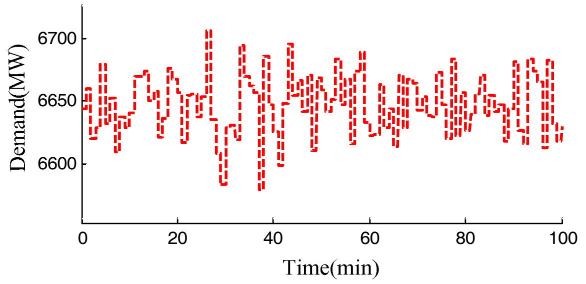

Fig. 8. Sample demand profile.

The aggregated demand of 17 load buses is generated through the normally distributed random process. The variances of this demand profile and the sampling period of are set to 1/18 and 1 min, respectively. A demand profile of 100 min is shown in Fig. 8. Furthermore, the simulations are performed using Matlab/Simulink software.

The simulations consist of three cases, as provided in Table 3. Case I represents the general power system without the V2G scheme, and Case II is a simple, price-based V2G scheme that cannot manage its SOC efficiently. Case III is the proposed price-based V2G scheme that has the SOC controller installed on the battery system. The controller parameter values for the three cases are listed in Table 2.

The aggregated battery capacity of V2GSE is assumed to be 120 MWh in all cases. The price generating process $K(s)$ is chosen from [13] as

$$K(s) = 2.61\left(1 + \frac{1}{10s} + 3s\right). \tag{6}$$

The parameter values of the aggregated battery system change depending on the number of parked EVs. However, the altered parameter values rarely affect the dynamics of this system [9]. Therefore, the parameters are presumably fixed in the simulation as provided in Table 3.

Table 2. Controller parameter values for three cases.

	Description	Battery management controller
Case I	No V2G	-
Case II	V2G without battery management controller	-
Case III	V2G with battery management controller	$3\times10^{-4}\left(1+\frac{1}{s}+\frac{4}{3}s\right)$

Table 3. Parameters for the virtual aggregated electric battery system of V2GSE.

Parameter	Value
Battery input gain	1
V2G activation delay, T_d	4 s
Battery filter time constant	1
Series resistance, R_{series}	0.013 Ω
Transient capacitance, C_t	100 F
Transient resistance, R_t	0.001 Ω
Battery output gain	5×10^{-5}
Battery initial charge, CR_0	60%
Battery operation ranges	20%-95%

4.2 Simulation results

The simulation results are displayed in Fig. 9. The magnified part of Fig. 9(a) indicates that the performance levels of the frequency regulation function are ordered as follows: Case I < Case II < Case III. In other words, the proposed scheme exerts the most useful effect on the frequency regulation function. . It is obviously that V2G resources can help frequency regulation function in power system comparing with Case I, even without battery suitable management controller. This result also implies that the charging and discharging speeds of the aggregated battery system can be controlled more effectively at a proper time by the battery management controller than in Case III rather than Case II.

Fig. 9(b) depicts the clear difference between Case II and Case III in terms of the SOC of the battery system. In Case II, SOC fluctuates randomly because the battery system cannot manage its SOC. This fluctuation is undesirable in terms of battery life time and reliable V2G function. By contrast, the battery management controller reduces the excessive oscillation of SOC in Case III and maintains the SOC at roughly the scheduled value of 60%. As per these results, this study verifies that V2G can

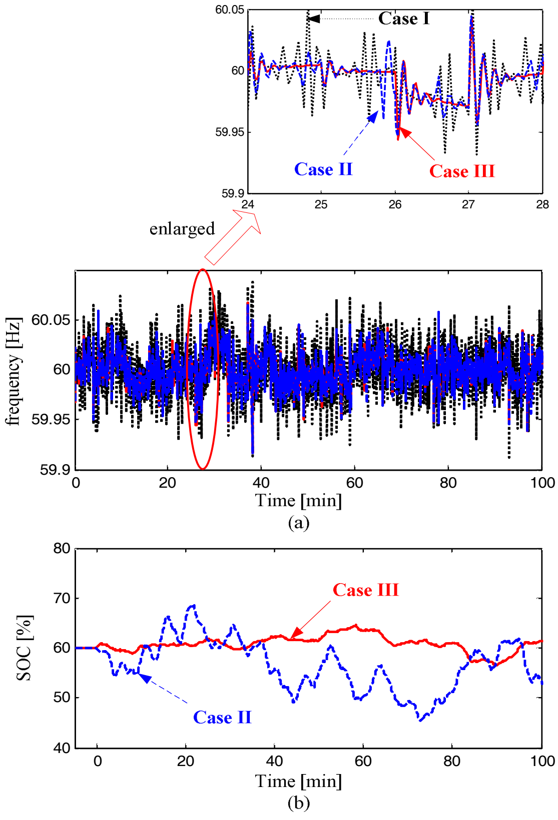

Fig. 9. Simulation results: (a) Frequency regulation results; (b) SOC of the aggregated battery system.

support the frequency regulation function within the PBO environment and that the proposed battery management controller operates effectively in a decentralized manner.

5. Conclusion

In this paper, a real-time control structure is proposed to implement the V2G system into the price-based scheme of power system operation effectively. The proposed structure specifies the structure of the battery management controller with two feedback loops; one is for SOC, and the other is for the real-time price. The threshold price is introduced to compare the difference between the current SOC and the pre-scheduled SOC with respect to real-time price. The final decision regarding charging/discharging can be made in the battery management controller based on the threshold price. In addition, the V2GSE battery management controller is designed to adjust its charging / discharging power based on its own residual energy in a decentralized manner. It is shown that the proposed method for V2G power can be very helpful for a frequency regulation function. It is also verified that the proposed structure is efficient for managing SOC in a decentralized operation scheme.

Acknowledgement

This work was supported in part by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP)(No. 2010-0028509) and in part by the Brain Korea 21 Plus Project in 2014.

References

[1] Pascal Mercier, Rachid Cherkaoui, and Alexandre Qudalov, “Optimizing a battery energy storage system for frequency control application in an isolated power system,” *IEEE Trans. Power Systems*, vol. 24, no. 3, pp. 1469-1477, 2009.

[2] K. C. Divya, and Jacob Østergaard, “Battery energy storage technology for power systems-An overview,” *Electric Power Systems Research*, vol. 79, no. 4, pp. 511-520, 2006.

[3] Minh Y Nguyen, Dinh Hung Nguyen, and Yong Tae Yoon, “A New Battery Approach to Wind Generation System in Frequency Control Market,” *Journal of Electrical Engineering & Technology,* vol. 8, no. 4, pp. 667-674, 2013.

[4] Jayakrishnan Radhakrishna Pillai, and Birgitte Bak-Jensen, “Vehicle-to-grid systems for frequency regulation in an Islanded Danish distribution network,” *Vehicle Power and Propulsion Conference (VPPC), 2010 IEEE*. IEEE, 2010.

[5] Jong-Uk Lee, Young-Min Wi, Youngwook Kim, and Sung-Kwan Joo, “Optimal Coordination of Charging and Frequency Regulation for an Electric Vehicle Aggregator Using Least Square Monte-Carlo (LSMC) with Modeling of Electricity Price Uncertainty,” *Journal of Electrical Engineering & Technology*, vol. 8, no. 6, pp. 1269-1275, 2013.

[6] Christophe Guille and George Gross, “A conceptual framework for the vehicle-to-grid (V2G) implementation,” *Energy Policy,* vol. 37, no. 11, pp. 4379-4390, 2009.

[7] Hui Liu, Zechen Hu, Yonghua Song, and Jin Lin, “Decentralized Vehicle-to-Grid Control for Primary Frequency Regulation Considering Charging Demands,” *IEEE Trans. Smart Grid,* vol. 28, no. 3, pp. 1-10, 2013.

[8] Sekyung Han, Soohee Han, and Kaoru Sezaki. “Development of an optimal vehicle-to-grid aggregator for frequency regulation,” *IEEE Trans. Smart Grid,* vol. 1, no. 1, pp. 65-72, 2010.

[9] Jayakrishnan Radhakrishna Pillai, and Birgitte Bak-Jensen. “Integration of vehicle-to-grid in the western Danish power system,” *IEEE Trans. Sustainable Energy,* vol. 2, no. 1, pp. 12-19, 2011.

[10] Andrej Jokić, E. H. M. Wittebol, and P. P. J. Van den Bosch, “Dynamic market behavior of autonomous *network-based power systems,*” *European Trans. Electrical Power,* vol. 16 , no. 5, pp. 533-544, 2006.

[11] Andrej Jokić, Mircea Lazar, and P. P. J. Van den Bosch. “Real-time control of power systems using nodal prices,” *International Journal of Electrical Power & Energy Systems*, vol. 31, no. 9, pp. 522-530, 2009

[12] Wei-Yu Chiu, Hongjian Sun, and H. Vincent Poor. “Energy Imbalance Management Using a Robust Pricing Scheme,” *IEEE Trans. Smart Grid,* vol. 4, no. 2, pp. 896-904, 2013.

[13] Young Gyu Jin, See Young Lee, Seung Wan Kim, and Yong Tae Yoon, “Designing Rule for Price-Based Operation With Reliability Enhancement by Reducing the Frequency Deviation,” *IEEE Trans. Power Systems,* vol. 28, no. 4, pp. 4365-4372, 2013.

[14] Seung Wan Kim, Young Gyu Jin, Hyeong Ig Kim, and Yong Tae Yoon, “Decentralized Price-based Vehicle-to-Grid Operation Scheme for Frequency Regulation,” International Conference of Electrical Engineering, 2014.

[15] Min Chen, and Gabriel A. Rincon-Mora. “Accurate electrical battery model capable of predicting runtime and IV performance,” *IEEE Trans. Energy conversion,* vol. 21, no. 2, pp. 504-511, 2006.

[16] John Chiasson and Baskar Vairamohan, “Estimating the state of charge of a battery,” *IEEE Trans. Control Systems Technology*, vol. 13, no. 3, pp. 465-470, 2005.

[17] Fernando Alvarado, J. Meng, C.L. DeMarco, and W.S. Mota, “Stability analysis of interconnected power

systems coupled with market dynamics," *IEEE Trans. Power Systems*, vol. 16, no. 4, pp. 695-701, 2001.
[18] Dimitri P. Bertsekas, Dynamic Programming and Optimal Control, vol. I, MIT, 1995.
[19] Fernando Alvarado, "The stability of power system markets," *IEEE Trans. Power Systems,* vol. 14, no. 2, pp. 505-511, 1999.

Seung Wan Kim He received B.S degree in electrical engineering from Seoul National University in 2012. Currently, he is working on Doctor's course in SNU. His research interest is Decentralized operation, Micro-grid Planning, Battery Energy Storage System.

Young Gyu Jin He received B.S., M.S., and Ph.D. degrees in Electrical Engineering from Seoul National University in 1999, 2001, and 2014, respectively. He had worked for KT Inc. during 2002-2010. Currently, he is a research professor at WeGAT center, Chonbuk National University. His research interests include operation of smart grid/microgrid, wind farm control, and power economics.

Yong Hyun Song He received B.S degree in electrical engineering from Seoul National University in 2013. Currently, he is working on Doctor's course in SNU. His research interests are Micro-grid operation, Unit Commitment, Energy Storage System.

Yong Tae Yoon He received his B.S., M. Eng., and Ph.D. degrees from M.I.T., USA in 1995, 1997, and 2001, respectively. Currently, he is a Professor in the Department of Electrical and Computer Engineering at Seoul National University, Korea. His research interests include power economics, smart grid/microgrid, and decentralized operation.