J Electr Eng Technol.2018; 13(?): 1921-718 http://doi.org/10.???/JEET.20

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

# Lifetime Management Method of Lithium-ion battery for Energy Storage System

**Il-Kuen Won*, Kyoung-Min Choo*, Soon-Ryung Lee*, Jung-Hyo Lee** and Chung-Yuen Won†**

**Abstract** – The lifetime of a lithium-ion battery is one of the most important issues of the energy storage system (ESS) because of its stable and reliable operation. In this paper, the lifetime management method of the lithium-ion battery for energy storage system is proposed. The lifetime of the lithium-ion battery varies, depending on the power usage, operation condition, and, especially the selected depth of discharge (DOD). The proposed method estimates the total lifetime of the lithium-ion battery by calculating the total transferable energy corresponding to the selected DOD and achievable cycle (ACC) data. It is also demonstrated that the battery model can obtain state of charge (SOC) corresponding to the ESS operation simultaneously. The simulation results are presented performing the proposed lifetime management method. Also, the total revenue and entire lifetime prediction of a lithium-ion battery of ESS are presented considering the DOD, operation and various condition for the nations of USA and Korea using the proposed method.

**Keywords**: Energy storage system, Lithium-ion battery, Lifetime, Depth of discharge, Achievable cycle

Proofreading

## 1. Introduction

Recently, research on the smart grid that combines Information & Communication Technology (ICT) with the power system has actively progressed around the world, resulting in developments such as renewable energy power plants, plug-in electric vehicles, and ESS. These developments are based on electrochemical batteries, playing a key role in resources exploitation as well as energy consumption optimization. [1, 2] ESS is currently used for different applications including peak-shaving, load-leveling, and power quality improvement as well as to support the of renewable energy sources connected to the grid as distributed generation. [3-5]

The ESS system performs efficient energy consumption by selecting the optimal time of battery charging and discharging considering the power requirement and power production. Therefore, efficient energy management is available by using the ESS performing peak-shaving and load leveling. Also, the electricity rates in accordance with the battery discharging operation provide economic profit to the ESS user. [6]

Fig. 1 shows the general configuration of the ESS. The system is composed of a bi-directional DC-DC converter for controlling the current of the battery and DC/AC PWM converter for supplying power to the grid and load. Research on power conversion devices and control algorithms for the grid-tied system using a lithium-ion battery are currently being carried out. [7-11]

In the configuration of ESS, a secondary battery is essential to perform the charge and discharge operation. Indeed, the efficiency and characteristics of the secondary battery determine the performance of the ESS. Among the various secondary batteries, the production of lithium-ion batteries has been continually increasing because of their excellent performance, which is related to their high specific energy, energy density, specific power, efficiency, and long lifetime. [12, 13] Especially, in consideration of the volume of the total system including the battery, the advantage of the lithium-ion battery that is applied to the ESS is maximized. When the ESS system is configured, the lifetime of the lithium-ion battery is an important issue

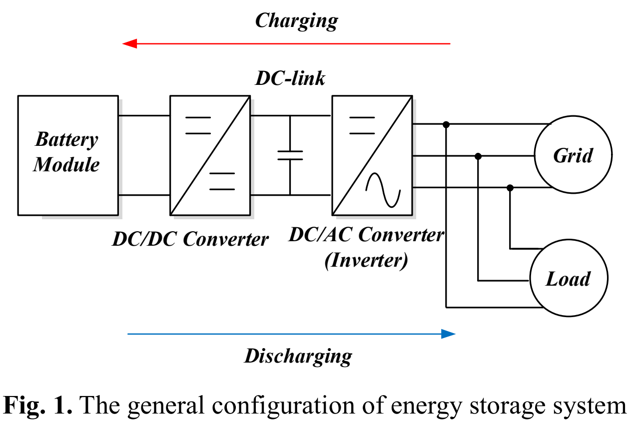



**Fig. 1.** The general configuration of energy storage system

† Corresponding Author: Dept. of Electrical and Computer Engineering, Sungkyunkwan University, Korea. (woncy@skku.edu)
* Dept. of Electrical and computer Engineering, Sungkyunkwan University, Korea. ({ganzipers, chuchoo, nuckeub}@skku.edu)
** Dept. of Electrical Engineering, Kunsan University, Korea. (jhlee82@kunsan.ac.kr)
Received: March 1, 2017; Accepted: December 14, 2017



Copyright ⓒ The Korean Institute of Electrical Engineers
This is an Open-Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (http://creativecommons.org/licenses/by-nc/3.0/) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

in terms of the maintenance and reliability of the total system. When ESS is operated only considering the load condition or electricity rates, a lifetime of the battery cannot be taken into account.

However, if the lifetime of the lithium-ion battery can be predicted, stable it is possible to ensure stable operation over the lifetime of the lithium-ion battery. Also, estimating the entire lifetime of the lithium-ion battery is essential for estimating the actual total revenue prediction.

Therefore, the total transferable energy during the entire lifetime of battery should be calculated. The total transferable energy representing the amount of available battery power for charging and discharging during the entire lifetime vary according to the selected DOD because the ACC is affected by the selected DOD. In general, the ACC of a lithium-ion battery decreases in accordance with the increasing DOD.[14]

Therefore, in order to calculate the total transferable energy of the lithium-ion battery, fixed DOD control is needed. [15] And, in order to estimate the entire lifetime of the lithium-ion battery, the accurate information for the SOC of the lithium-ion battery of ESS is also required. SOC estimation methods have been extensively studied in the literature [16-22].

Also, because the chemical properties of the lithium-ion battery are significantly reduced at low temperature, the battery lifetime is adversely affected. [23-25] The general temperature range for safe operation of the lithium-ion battery is between -20 and 60°C, and most lithium-based batteries cannot be operated at a temperature below -20°C.

In general, the optimized temperature for maximizing the ACC of the lithium-ion battery is room temperature, 25°C. A heating and cooling device is therefore needed to ensure a constant temperature control of the lithium-ion battery system.

In this paper, the battery lifetime management method, which estimates the residual power and lifetime of the lithium-ion battery through total transferable energy is proposed considering in the room temperature. In order to control DOD, the improved battery model combining the Thevenin and Shepherd battery models is applied for open circuit voltage (OCV) and state of charge (SOC) calculation. [26]

This paper is arranged as follows: Section 2 explains the general system topology of grid-tie ESS system and the modes of power flow corresponding to the condition of the load and grid; Section 3 discusses the achievable cycle of lithium-ion battery and total transferable energy that can be calculated from the selected DOD; Section 4 presents the battery lifetime estimation method ; Section 5 explains the SOC estimation in order to obtain accurate battery voltage corresponding to the battery charging and discharging operation using the battery modeling. Section 6 gives the proposed battery lifetime management method. Section 7 provides simulation results for evaluating the performance of proposed method and estimating the total revenue and entire lifetime of a lithium-ion battery of ESS corresponding to the various condition, and Section 8 draws some conclusion.

## 2. Grid-tied ESS System

Grid-tied ESS have been studied in various topologies including single-phase and three-phase. Fig. 2 shows the configuration of Grid-tied energy storage system in this paper. The full-bridge converter is operated during the battery charging and discharging operation. It is commonly used an isolated DC/DC converter in consideration of the stability of the battery. The AC/DC PWM converter is operated as 3-phase rectifier mode at battery charging from the grid power. Also, it is operated as 3-phase inverter mode at battery discharging operation.

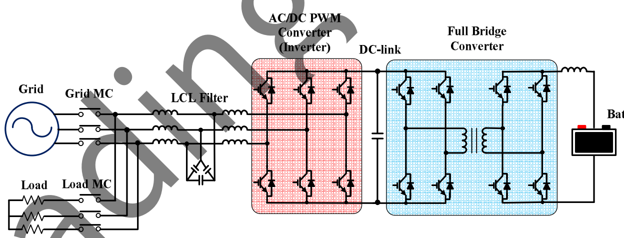



**Fig. 2.** The configuration of Grid-tied Energy storage system

Using the grid and load MC, the battery discharging power is transferred to the load or grid. The grid is connected directly to the load. The grid power is used for charging the battery or handling load. The ESS discharges the power from the battery to load and transmits the power to the grid during peak-load or charges the power to the battery during light-load.

Fig. 3 shows the mode of power flows that can be generated considering the load and system conditions.

Fig. 3(a) and 3(b) show the power flows mainly occurring during peak-load. At this time, the power of the battery handles the load and extra power provides the economic profit to the user by transmitting to the grid. Also, when the load is increased much more than battery power, both battery and grid should handle the load as seen in Fig3(c). Fig. 3(d) and 3(e) show the mode occurring during light-load. The battery is charged from the grid power and the grid handles the load.

## 3. Achievable Cycle of Lithium-ion Battery

Table 1 shows the achievable cycle data of the unit cell of the lithium-ion battery. The achievable cycle refers to the number of cycles during the entire lifetime of the lithium-ion battery in the condition of fixed DOD and temperature.

In general, the life cycle of the lithium-ion battery is

Proofreading

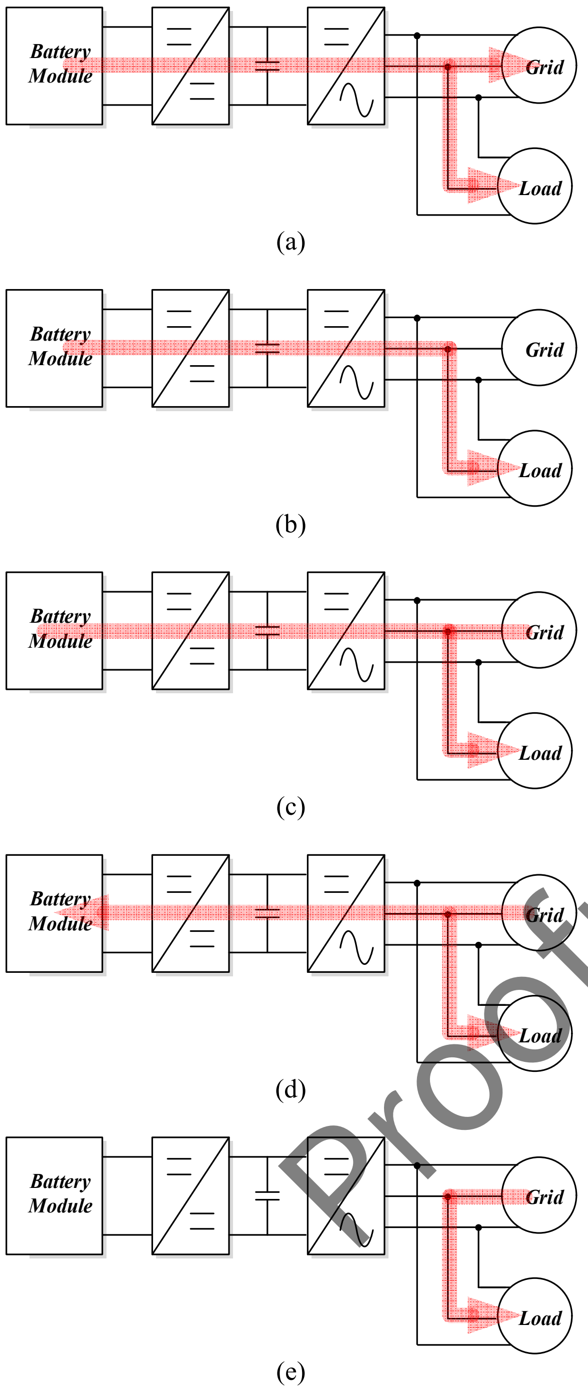



**Fig. 3.** The power flow of grid-tied ESS

**Table 1.** The achievable cycle data of unit cell of lithium-ion battery (ICR18650-22F)

| 0.5C Charge & Discharge Condition | | | | |
|---|---|---|---|---|
| DOD \ Temperature | 25 | 35 | 45 | 55 |
| 10% | 15,000 | 14,700 | 14,100 | 12,750 |
| 20% | 10,000 | 9,800 | 9,400 | 8,500 |
| 50% | 6,000 | 5,880 | 5,640 | 5,100 |
| 70% | 5,000 | 4,900 | 4,700 | 4,250 |
| 100% | 4,000 | 3,920 | 3,760 | 3,400 |

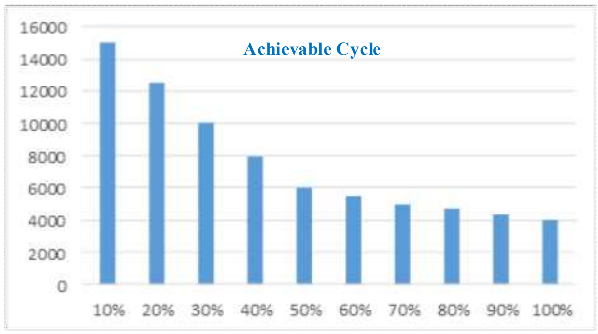



**Fig. 4.** The ACC of lithium-ion battery corresponding to the DOD

increased when low DOD is used [14]. Also, the lithium-ion battery has the most stable characteristics at room temperature because of the chemical change of the electrolyte of the lithium-ion battery at high and low temperature. Therefore, an additional heating device needs to be implemented to maintain a constant temperature for the stable operation of the lithium-ion battery at the low-temperature condition.

Fig. 4 shows the achievable cycle of the lithium-ion battery according to the battery operation at fixed DOD at room temperature. When only the load condition is considered when operating the ESS system, and when only the electricity rates are considered when charging and discharging power is computed, the lifetime of the lithium-ion battery cannot be taken into account. However, the lifetime of the lithium-ion battery is the most important variable in the operation of ESS considering the reliability and total lifetime of the entire system. In addition, the revenue of the ESS is determined based on the amount of battery power. In order to define the lifetime of the lithium-ion battery using the achievable cycle and DOD, the total transferable energy of battery must be calculated. [15]

The total transferable energy during the entire lifetime of the lithium-ion battery according to the selected DOD is calculated using Eq. (1). Here, D is the selected DOD, and Cycle(D) is the achievable cycle at the selected DOD. The power that can be used by the battery according to DOD is defined as D× Battery power.

1 cycle is defined as the operation of discharging and charging to the amount of selected DOD from the maximum SOC. Therefore, the two that describes the charging and discharging operation should be multiplied. Efficiency refers efficiency of PCS (Power conversion system) and this is not taken into account in this paper.

$$\begin{aligned}&\mathit{Total\ transferable\ energy}\\&=\mathit{Cycle}(D)\times 2\times D\times \mathit{Battery\ power}\times \mathit{efficiency}^2\end{aligned} \quad (1)$$

Fig. 5 shows the total transferable energy according to the selected DOD using the data of Fig.4. In order to calculate the total transferrable energy of the battery, the

Proofreading

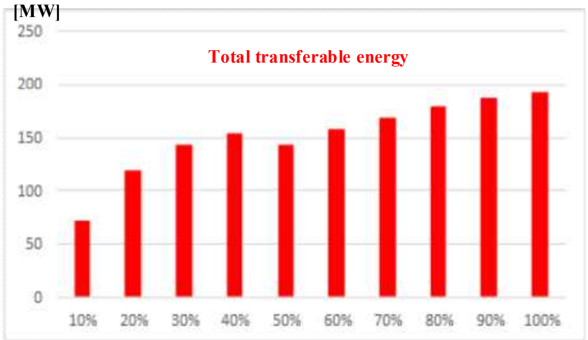



**Fig. 5.** The total transferable energy corresponding to the DOD

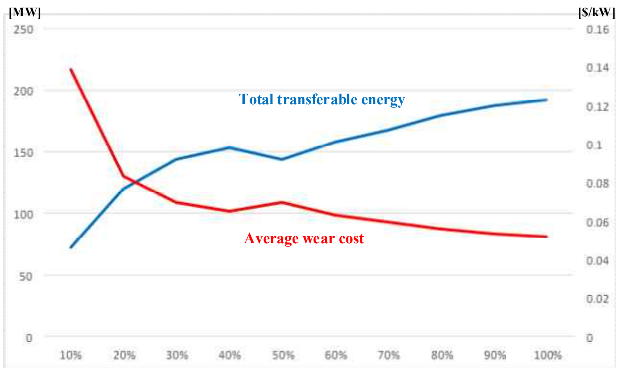



**Fig. 6.** Average wear cost corresponding to the DOD

power of the battery was selected as 24kW. As seen in Fig. 5, DOD having the highest value of total transferable energy is 100%, and the total transferable energy having different values corresponding to the selected DOD.

Depending on the chemical characteristics and the different types of battery, the achievable cycle corresponding to the selected DOD has different values. Therefore, the DOD having the highest value of the total transferable energy can differ, depending on the type of lithium-ion battery. Therefore, on the basis of the cycle data of the battery to be used, the user can select the DOD corresponding to the total transferable energy.

The average wear cost refers to the cost per unit of battery power calculated by dividing the battery price into the total transferable energy calculated by Eq. (2).

Fig. 6 shows the average wear cost corresponding to the ACC and DOD assuming the battery price is 10,000$. Therefore, it is important to select the DOD with the highest value of total transferable energy and with the lowest average wear cost in order to achieve efficient battery use.

$$\text{Average wear cost} = \frac{\textit{Battery}\ \text{Price}}{\textit{Total transferable energy}} = \frac{\textit{Battery price}}{\textit{Cycle}(D) \times 2 \times \textit{DOD} \times \textit{Battery power}} \quad (2)$$

## 4. Proposed Lifetime Estimation Method

In order to estimate the lifetime using the total transferable energy, a scheduled battery charging and discharging operation is needed. Fig. 7 shows an example of the scheduled battery operation considering the electricity rates with time. The battery power is selected as 24kW. The charging is performed for 1 hour by 1 C-rate and the discharging is performed for 2 hours at 0.5 C-rates.

This approach can be the method for making the economic profit of ESS user by selecting the charging and discharging time corresponding to the electricity rates. When the daily battery operation pattern is established, it is possible to calculate the battery lifetime by comparing the total transferable energy at the selected DOD with the used battery power per year.

Used battery power per year can be given through (3), which is the sum of the daily power use of the battery for one year.

$$\textit{Used battery power} = \sum_{n=1}^{365} 2 \times N \times \textit{DOD} \times \textit{Battery power} \quad (3)$$

Here, N is the variable by which a user can select the number of operations of battery cycle for one day.

The battery in the ESS performs charging and discharging corresponding to the DOD selected by the user.

In order to calculate the residual battery lifetime through the total transferable energy and the used battery power per year, the battery should be operated for the selected DOD.

When the amount of annual battery power usage is determined, it is possible to predict the potential life of the battery through the total transferable energy. The residual battery lifetime can be calculated annually by (4).

$$\textit{Battery lifetime}(\textit{year}) = \frac{\textit{Total transferable energy}}{\textit{Used battery power}} \cong \frac{\textit{Cycle}(D) \times 2 \times \textit{DOD} \times \textit{Battery power}}{\sum_{n=1}^{365} 2 \times N \times \textit{DOD} \times \textit{Battery power}} \quad (4)$$

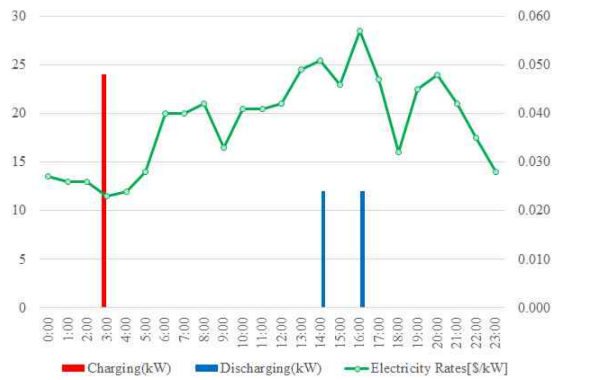



**Fig. 7.** Scheduled battery charging, discharging operation considering the electricity rates

Proofreading

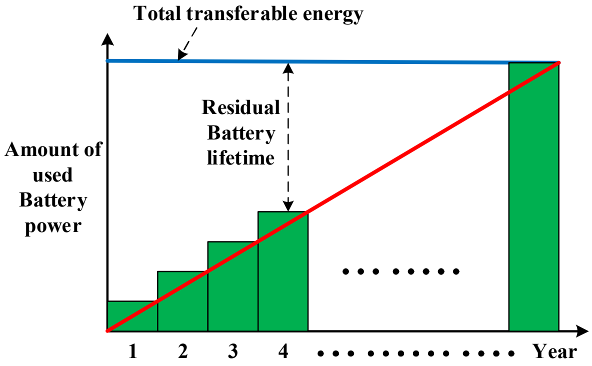



**Fig. 8.** Schematic of residual battery lifetime estimation

Therefore, the charging and discharging operation of the battery should be performed to the amount of DOD selected by the user in order to calculate the total transferable energy.

Also, in order to manage the lifetime of the battery, scheduled battery charging and discharging control should be performed for the selected DOD. Therefore, accurate SOC information is required corresponding to the battery operation.

## 5. SOC Estimation

The SOC estimation methods using a battery model have been extensively studied in the literature [16-22]. The Thevenin model represents the discharge or charge voltage of a battery when it is assumed that the open circuit voltage (OCV) of the battery has a constant value or linearity. Although this method has been widely used, it has relatively low accuracy [20].

The Shepherd model has been used universally because it can reflect the OCV of diverse battery types. However, the transient characteristics of the battery cannot be represented because the Shepherd model includes only the internal resistance of the battery [21, 22].

The SOC estimation method in this paper is combined with a Coulomb counting method and battery model. The battery model is coupled with the Shepherd model and the Thevenin model. Fig. 9 shows the battery model coupled

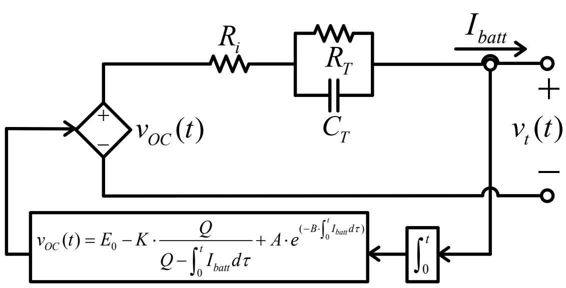



**Fig. 9.** Battery model coupled with Shepherd and Thevenin model

with the Shepherd and the Thevenin model.

Battery model can be implemented by a simple electric circuit that can describe the actual nonlinear V-I characteristics of the battery. Battery terminal voltage can be obtained by calculating the battery open circuit voltage. Therefore, nonlinear variables of the battery need to be assigned. The Shepherd model which represents the electrochemical battery can be expressed as

$$v_{OC}(t) = E_0 - K \cdot \frac{Q}{Q - \int_0^t I_{Batt} d\tau} + A \cdot e^{(-B \cdot \int_0^t I_{Batt} d\tau)} \tag{5}$$

$$E_o = E_{Full} + K + R_i \cdot I_{Batt} - A \tag{6}$$

$$A = E_{Full} - E_{Exp}, \quad B = \frac{3}{Q_{Exp}} \tag{7}$$

$$K = \frac{(E_{Full} - E_{Nom} + A(\exp(-B \cdot Q_{Nom}) - 1)) \cdot (Q - Q_{Nom})}{Q_{Nom}} \tag{8}$$

where $v_{OC}(t)$ is the open circuit voltage, $E_0$ is the battery constant voltage, $K$ is the polarization voltage, $A$ is the exponential zone amplitude, and B is the exponential zone time constant inverse of the battery module.

The specification of the one cell of the lithium-ion battery is described in Table 2.

In the case of connecting the 24-series and 5-parellel of the unit cell, $E_{Full}$ is the fully charged voltage of the battery module, where two lead-acid battery packs are connected in series (=100.8). $E_{Exp}$ is the exponential zone voltage of the battery module (=98.08V), and $E_{Nom}$ is the nominal zone voltage of the battery module (=92.5V). $Q$ is the total capacity of the battery module, which is 10Ah in order to adjust the time scale for the discharge curve. $Q_{Exp}$ is the capacity in the exponential zone of the battery module (=1Ah), and $Q_{Nom}$ is the capacity of the battery module up to the nominal zone (=9Ah). $R_i$ is the internal resistance of the battery module (=0.005Ω).

The Thevenin battery model with parallel RC circuits is

**Table 2.** Specification of unit cell of a lithium-ion battery

| Item | Battery type | Battery capacity | Nominal voltage | Full charged voltage | Internal resistance |
|---|---|---|---|---|---|
| Rating | Lithium-ion | 2Ah | 3.7V | 4.2V | 0.005Ω |

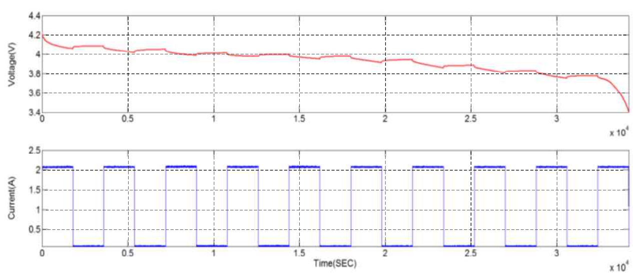



**Fig. 10.** OCV measurement test

Proofreading

**Table 3.** OCV corresponding to the SOC

| SOC | OCV |
|---|---|
| 100 | 4.2 |
| 90 | 4.087 |
| 80 | 4.053 |
| 70 | 4.013 |
| 60 | 3.99 |
| 50 | 3.98 |
| 40 | 3.945 |
| 30 | 3.88 |
| 20 | 3.83 |
| 10 | 3.77 |
| 0 | 3.47 |

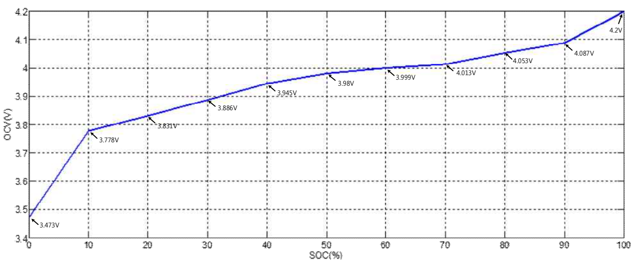



**Fig. 11.** OCV measurement corresponding to the SOC

added to represent the behavior characteristic corresponding to the change in the transient load so that this model can express the physical properties of the battery.

Finally, for the battery terminal voltage $v_t(t)$ is given as where $R_T$ is the transient resistance and $C_T$ is the transient capacitance.

$$v_t(t) = v_{OC}(t) - i_{batt}(t)\left[R_i + (C_T // R_T)\right] \quad (9)$$

Fig. 11 and Table 3 shows the OCV of the unit cell of the lithium-ion battery used in this paper.

## 6. Proposed Battery Lifetime Management Method

Fig. 12 shows the flow diagram of the proposed battery lifetime management. In order to predict the lifetime of the battery, the fixed DOD and daily cycle for the battery operation need to be assigned. As the DOD is selected, the total transferable energy is calculated using the selected DOD and the number of achievable cycles corresponding to the selected DOD.

The daily battery power usage can be calculated according to the daily battery cycle. Through the above process, the battery lifetime is estimated by comparing the total transferable energy and the daily power usage of the battery using Eq. (4).

If the estimated lifetime differs from the lifetime desired by that user of ESS, the DOD or daily cycle selection should be re-established. In addition, if the DOD and the

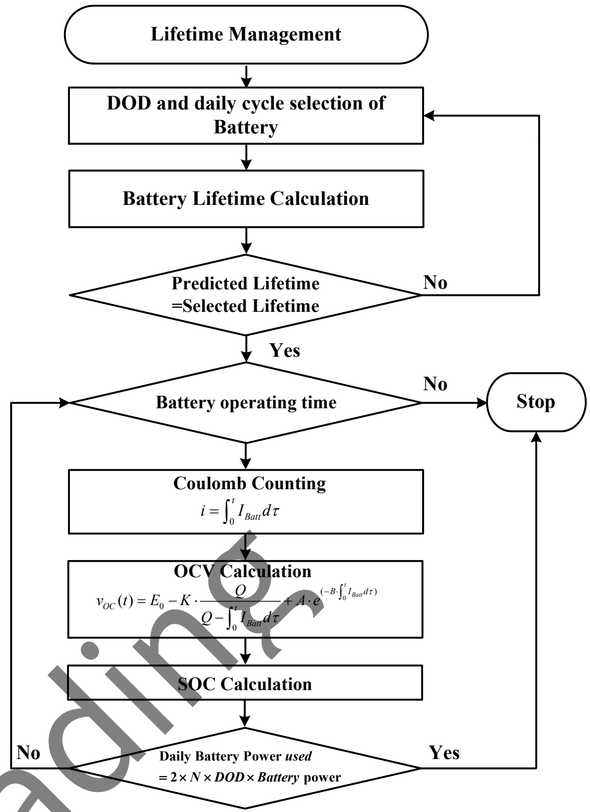



**Fig. 12.** Flow diagram of proposed lifetime management

daily cycle of the battery are established, scheduled battery operation time performing the battery charging and discharging should be selected.

The charging and discharging time of the battery can be set in consideration of the user's requirements, such as electricity rates or load pattern, etc. The taking time for charging and discharging is varied depending on the C-rate.

Therefore, C-rate should be selected depending on the scheduled battery operation time. After determining the above condition, the battery operates in the selected battery operation time.

In order to apply the proposed method, DOD of battery should be controlled accurately. Therefore, the OCV calculation corresponding to the battery operation should be performed. At the battery operating time, the battery is charged first, charging to the maximum SOC, and the battery charging current is calculated by coulomb counting. Thereafter, SOC is obtained corresponding to the OCV calculation.

After battery charging, because of the daily use of battery power is smaller than the user's setting, the discharging operation of battery should be performed. The battery is discharged at discharging operation time, and the battery should not be operated when the SOC of the battery is reached at the selected DOD. Thereafter, the amount of daily power usage of the battery has the same value that in the user's setting, and it should be operated up to the operation time of the next day.

Proofreading

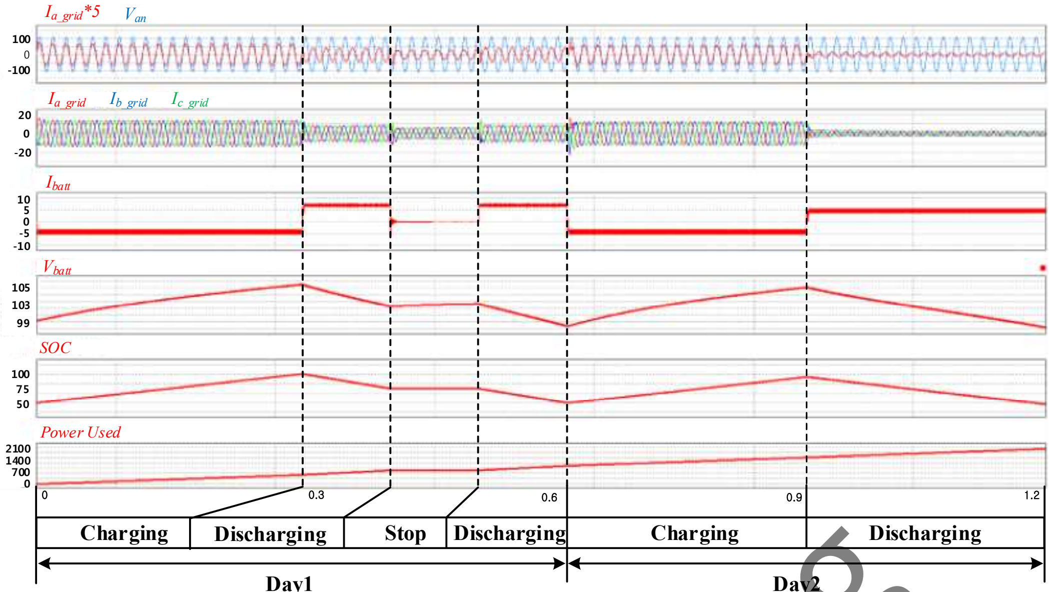
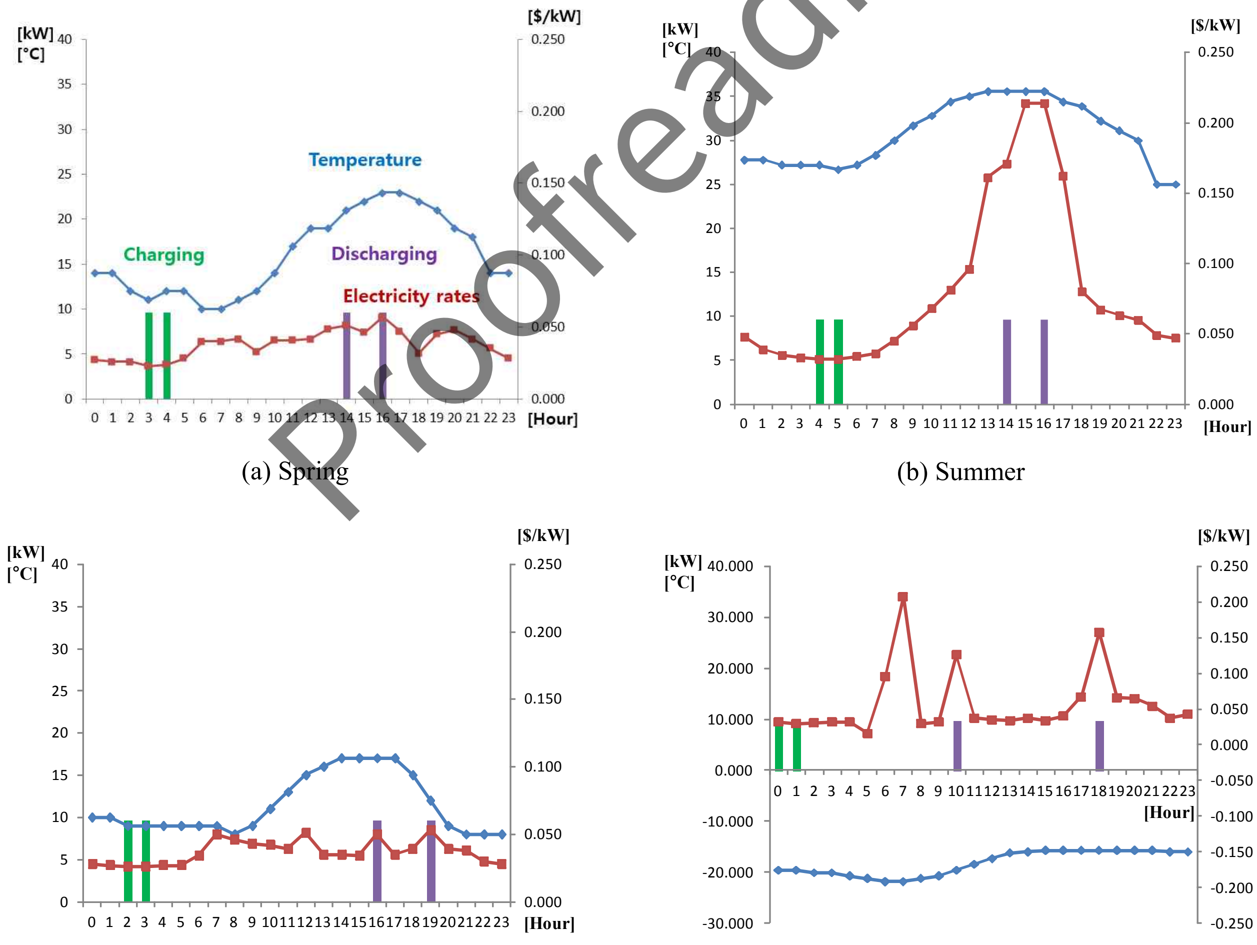



**Fig. 13.** The waveforms applying proposed method and battery model of grid-tied ESS at DOD 50%




(a) Spring (b) Summer

(c) Fall (d) Winter

**Fig. 14.** Electricity rates, temperature, charging and discharging patterns at DOD 80% of the Illinois (USA) of each season

Proofreading

## 7. Simulation Results

Fig. 13 shows the waveforms applying the proposed method and battery the model of grid-tied ESS at a DOD of 50%. The waveforms describe the 1 cycle per day operation using the proposed lifetime management method over 2 days. It is assumed that the battery module is composed of a 24-series, 5-parallel connection of the unit cell of lithium-ion battery in Table 2.

In order to describe 1 cycle of charging and discharging per day operation, 1 hour is mathematically expressed as 0.3 seconds. At day 1, the battery is first charged at a 0.5 C-rate, accordingly, and the battery SOC and the amount of battery power used are calculated. After the charging operation, and up to when the SOC reaches 100%, the battery is discharged to DOD 50%. Because of the lifetime estimation considering the ACC and DOD, the DOD should be controlled to be constantly 50%. The amount of daily power used calculated at DOD 50% is 1kW.

It was confirmed that this simulation value matches the calculated value. At day 2, it is operated within the DOD 50%. Therefore, lifetime management is possible using the proposed method.

The potential revenues and lifetime of the lithium-ion battery of ESS can, therefore, be estimated with the information between the DOD and ACC. Figs. 14 and 15 show the electricity rates, temperature, and charging and discharging patterns at DOD 80% of the Illinois (USA) and Korea seasons. Electricity rates that are used in the simulation are based on the Illinois, 'Residential Real-Time Pricing (RRTP) program, which is sourced from the Exelon that supplies 80% of the total power of the United States and from the Korea Electric Power Corporation (KEPCO).

The selected DOD is 80% and the selected battery power is 24kW. Also, C-rate was fixed at 0.5 for the stable charging and discharging operation of the battery. In addition, the charging and discharging patterns optimized for the electricity rates of each season were applied to achieve efficient energy use for the user and 1 cycle per day of charging and discharging was performed at the selected DOD of 80%.

Based on the hourly electricity rates of each nation, the user can obtain maximum revenue by charging the battery at the minimum electricity rates hours and discharging it

Proofreading

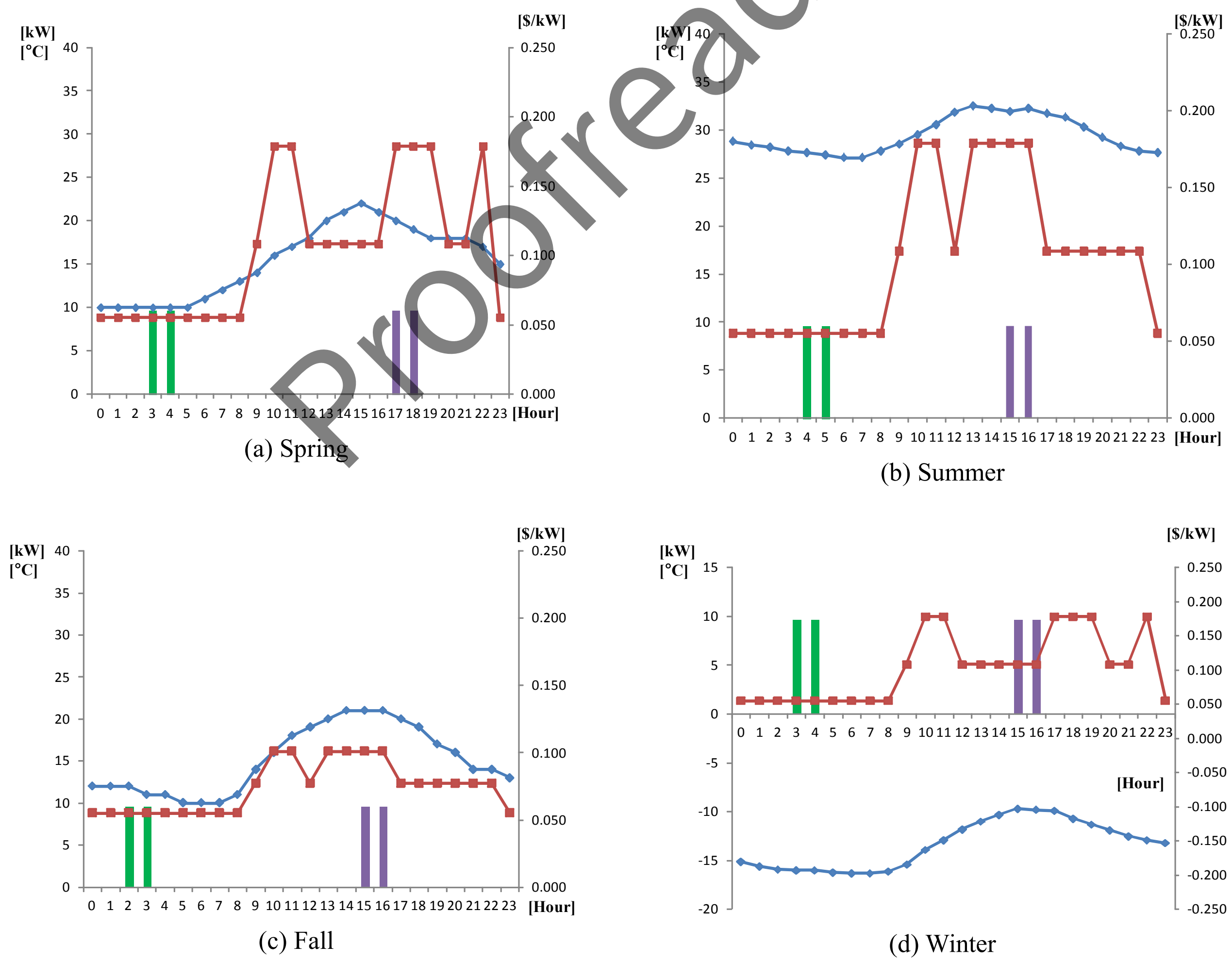



**Fig. 15.** Electricity rates, temperature, charging and discharging patterns at DOD 80% of the Korea of each season

maximum electricity rates hours, respectively. Also, during some hours, temperature falls below –20°C in the winter, charging and discharging were not performed during such hours.

Examining the electricity rates for the summer and winter seasons of USA, greater differences are shown in the electricity rates per hour than for the spring and fall seasons. This means that daily revenue from the operation of ESS increase in the summer and winter. The cycle and total transferable energy calculation results are given in Fig. 4 and Fig. 5, respectively. The achievable cycle and total transferrable energy at DOD 80% are approximately 5000 and 192MW in both nations. The daily battery power per day is the same: 40kW, because of the same DOD operation. Therefore, the annual battery power consumption is calculated as 14.6MW and the estimated potential lifetime of the lithium-ion battery is 13.6 years at this condition.

For the potential revenue analysis, if the efficiency of PCS of ESS system is ideal that means the system efficiency is 100%, the electricity rates for battery charging / discharging are both calculated simply as seen in Eq. (10).

$$\begin{aligned}&\textit{Electricity rates for battery operation}\\&= D \times \textit{Battery power} \times \textit{Electricity rates}\end{aligned} \tag{10}$$

Indeed, the efficiency of the PCS results in a change in potential revenue analysis. At considering the system efficiency of PCS, the electricity rates for battery charging operation can be expressed as (11), where $\eta$ is the efficiency of the PCS.

$$\begin{aligned}&\textit{Electricity rates for battery charging}\\&= D \times \textit{Battery power} \times \textit{Electricity rates}\\&\quad + D \times \textit{Battery power} \times \textit{Electricity rates}(1-\eta)\\&= D \times \textit{Battery power} \times \textit{Electricity rates}(2-\eta)\end{aligned} \tag{11}$$

As the same way, the electricity rates for battery discharging operation can be calculated by the (12).

$$\begin{aligned}&\textit{Electricity rates for battery discharging}\\&= D \times \textit{Battery power} \times \textit{Electricity rates}\\&\quad - D \times \textit{Battery power} \times \textit{Electricity rates}(1-\eta)\\&= D \times \textit{Battery power} \times \textit{Electricity rates} \times \eta\end{aligned} \tag{12}$$

Potential revenue prediction is varied depending on the efficiency of the PCS of the ESS system used by the user. Therefore, establishing a high-efficiency ESS system is very important for high profits to user. In this paper, for prediction of the potential revenue of the Illinois and Korea, it is assumed that the efficiency of the PCS is ideal.

As a result, the daily revenues of \$0.586, \$3.494, \$0.499 and \$3.052 were obtained in the spring, summer, fall, and winter in Illinois, respectively. In addition, the daily revenues of \$2.371, \$2.371, \$0.879 and \$2.371 were obtained in the spring, summer, fall, and winter in Korea respectively. With this method, the annual revenue is calculated to be \$695 and \$729 in Illinois and Korea, respectively. Therefore, the potential total revenue during the entire lifetime of a lithium-ion battery for each nation can be predicted to be \$8,887 and \$9,330, respectively at this condition. The predicted total revenue and lifetime of ESS using the proposed method are changed corresponding to the selected DOD and the daily cycle as well as the various types of the lithium-ion battery. Therefore, the user can estimate the various results corresponding to the above variables.

Figs. 16 and 17 show the revenue prediction of each season and 1 year corresponding to the different DODs of Illinois and Korea, from the above electricity rates condition of Figs. 14 and 15. According to the different selected DODs, the natural, seasonal and annual revenue significantly increase corresponding to the increasing DOD.

Considering the inversely proportional relation of the estimated total lifetime and DOD, the total revenue calculation during the entire lifetime of the battery should be performed considering the entire area of DOD.

Fig. 18 shows the total revenue and entire lifetime

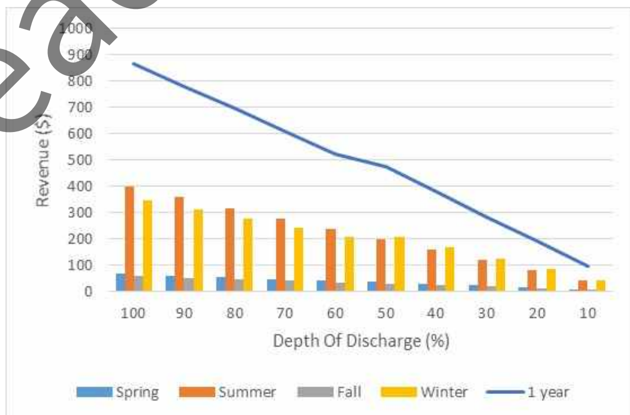



**Fig. 16.** Revenue prediction of seasonal and 1 year corresponding to the DOD in Illinois

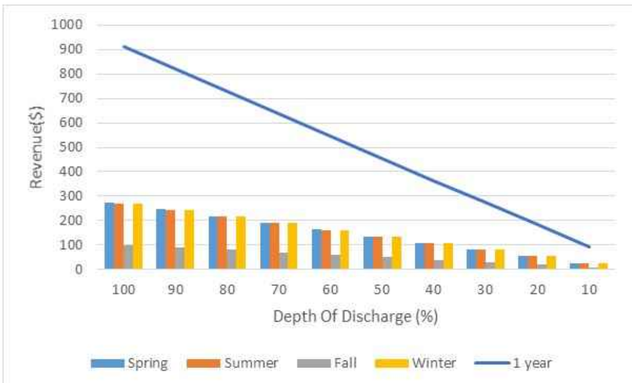



**Fig. 17.** Revenue prediction of seasonal and 1 year corresponding to the DOD in Korea

Proofreading

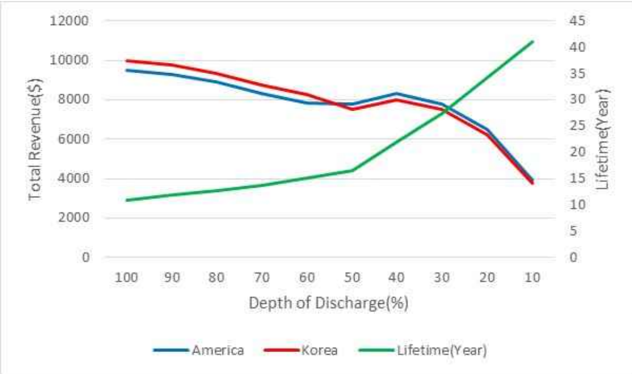



**Fig. 18.** Total Revenue and lifetime prediction of Illinois and Korea

prediction of Illinois and Korea. Total revenue is calculated by multiplying the annual revenue and lifetime with the selected DOD. The total revenue seems to decrease in accordance with the decreasing DOD, but the total revenue of DOD 40% has the higher value than to the 50%.

## 8. Conclusion

In this paper, the battery lifetime management method of the lithium-ion battery for energy storage system is proposed. Generally, the ACC is increased corresponding to the decreasing DOD. The lifetime of the lithium-ion battery and the total transferrable energy can be estimated based on DOD. The operations of the ESS and the lifetime management of selected DOD are given.

The total revenues are predicted over the lifetime of using a battery of ESS through proposed method. Therefore, depending on the proper selection of lithium-ion battery and DOD, the user can select the desired lifetime and profitability of the system.

## Acknowledgements

This work was supported by "Human Resources Program in Energy Technology" of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea. (No.20164030200980)

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy(MOTIE) of the Republic of Korea. (No. 20162010103830)

## References

[1] P. C. Loh, D. Li, Y. K. Chai, and F. Blaabjerg, "Hybrid AC–DC microgrids with energy storages and progressive energy flow tuning," *IEEE Transaction on Power Electronics*., vol. 28, no. 4, pp. 1533-1543, Apr. 2013.

[2] S. Huang, B. Huang, and F. Pai, "Fast charge strategy based on the characterization and evaluation of LiFePO4 batteries," *IEEE Transaction on Power Electronics*, vol. 28, no. 4, pp. 1555-1562, Apr. 2013.

[3] Theodore Soong, Peter W. Lehn, "Evaluation of Emerging Modular Multilevel Converters for BESS Applications," *IEEE Transactions on Power Delivery*, vol. 29, pp. 2086-2094, Oct. 2014.

[4] Matthew T. Lawder, Bharatkumar Suthar, Paul W. C. Northrop, Sumitava De, C. Michael Hoff, Olivia Leitermann, Mariesa L. Crow, Shriram Santhanagopalan, Venkat R. Subramanian, "Battery Energy Storage System (BESS) and Battery Management System (BMS) for Grid-Scale Applications," *Proceedings of the IEEE*, vol. 102, pp. 1014-1030, June. 2014.

[5] Yang Zhang, Herbert Ho-Ching Iu, Tyrone Fernando, Fang Yao, Kianoush Emami, "Cooperative Dispatch of BESS and Wind Power Generation Considering Carbon Emission Limitation in Australia," *IEEE Transactions on Industrial Informatics*, vol. 11, pp. 1313-1323, Dec. 2015.

[6] Raymond H. Byrne, C´esar A and Silva-Monroy, "Estimating the Maximum Potential Revenue for Grid Connected Electricity Storage: Arbitrage and Regulation," Sandia National Laboratories, 2012

[7] Xiaolei Hu, K. J. Tseng, Yitao Liu, Shan Yin, Mengqi Zhang, "A high frequency isolated current-fed bidirectional DC/AC converter for grid-tied energy storage system," *ECCE Asia*, pp. 291-296, 2013.

[8] Nagisa Takaoka, Jun-ichi Itoh, "Battery Energy Storage System with Isolated Single-phase Matrix Converter using Center-tapped Transformer for Power Decoupling Capability," *2015 International Conference on Renewable Energy Research and Applications*, pp. 1021-1026, Nov. 2015.

[9] Nadia Mei Lin Tan, Takahiro Abe, Hirofumi Akagi, "Design and Performance of a Bidirectional Isolated DC-DC Converter for a Battery Energy Storage System," *IEEE Transactions on Power Electronics*, vol. 27, pp. 1237-1248, Mar. 2012.

[10] Y. -C. Hsieh, C. -S. Huang, "Li-ion battery charger based on digitally controlled phase-shifted full-bridge converter," IET Power Electronics, vol. 4, pp. 242-247, Feb. 2011.

[11] Hao Qian, Jianhui Zhang, Jih-Sheng Lai and Wensong Yu, "A High-Efficiency Grid-Tie Battery Energy Storage System," *IEEE Transactions on Power Electronics*, vol. 26, pp. 886-896, Mar. 2011.

[12] Hossein Farzin, Mahmud Fotuhi-Firuzabad, Moein Moeini-Aghtaie, "A Practical Scheme to Involve Degradation Cost of Lithium-Ion Batteries in Vehicle-to-Grid Applications," *IEEE Transactions on*

Proofreading

*Sustainable Energy*, vol. 7, pp. 1730-1738, Oct. 2016.
[13] Mustafa Farhadi, Osama Mohammed, "Energy Storage Technologies for High-Power Applications," *IEEE Transactions on Industry Applications*, vol. 52, pp. 1953-1961, June. 2016.
[14] T. Guena, P. Leblanc "How Depth of Discharge Affects the Cycle life of lithium-Metal-Polymer Batteries," *INTLEC. 2006*, pp 1-8, Sept. 2006.
[15] Sekyung Han, Soohee Han, Hirohisa Aki, "A practical battery wear model for electric vehicle charging applications," *Applied Energy*, vol. 113, pp. 110-1108, Jan. 2014
[16] K.-C. Bae, S.-C. Choi, J.-H. Kim, Y.-C. Jung and C.-Y. Won, "LiFePO4 Dynamic Battery Modeling for Battery Simulator," *IEEE International Conference on Industrial Technology* (*ICIT*), pp. 354-358, Feb. 2014.
[17] S. Bhide and T. H. Shim, "Novel predictive electric Li-ion battery model incorporating thermal and rate factor effects," *IEEE Trans. Vehicular Tech.*, vol. 60, no. 3, pp. 819-829, Mar. 2011.
[18] M. Einhorn, F.V. Conte, C. Kral and J. Fleig, "Comparison, selection, and parameterization of electrical battery models for automotive applications," *IEEE Trans. Power Electron.*, vol. 28, no. 3, pp. 1429-1437, Mar. 2013.
[19] L. Lam and P. Bauer, "Practical capacity fading model for Li-ion battery cells in electric vehicles," *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5910-5918, Dec. 2013.
[20] M. Duerr, A. Cruden, S. Gair and J.R. McDonald, "Dynamic model of a lead-acid battery for use in a domestic fuel cell system," *Journal of Power Sources*, Vol. 161, no. 2, pp. 1400-1411, 2006.
[21] O. Tremblay, L.-. Dessaint and A.-. Dekkiche, "A Generic Battery Model for the Dynamic Simulation of Hybrid Electric Vehicles," *in Proc. IEEE Vehicle Power Propulsion Conf., 2007. VPPC 2007. IEEE*, 2007, pp. 284-289, Sept. 2007.
[22] J. S. Lee, J. J. Kim, M. R. Park, I. J. Park, "Electric Model of Li-Ion Polymer Battery for Motor Driving Circuit in Hybrid Electric Vehicle," *Journal of Electrical Engineering & Technology.*, vol. 7, no. 6, pp. 932-939, Nov. 2012.
[23] Yan Ji, Yancheng Zhang, and Chao-Yang Wang, "Li-Ion Cell Operation at Low Temperatures," *J. Electrochem*. soc. 2013, vol. 160, no. 4, pp. 636-649, Feb. 2013
[24] Jiang Fan, and Steven Tan, "Studies on Charging Lithium-Ion Cells at Low Temperatures," *J. Electrochem. soc. 2006*, vol. 153, no. 6, pp. 1081-1092, April 2013
[25] M. C. Smart, B. V. Ratnakumar, C. -K. Huang, and S. Surampudi, "Performance Characteristics of Lithium Ion Cells For Low Temperature Applications," Jet Propulsion Laboratory California Institute of Technology, 1998
[26] Il-Kuen Won, Do-Yun Kim, Jun-Ha Hwang, Jung-Hyo Lee, Chung-Yuen Won, "Lifetime management method of Lithium-ion battery for energy storage system," Electrical Machines and Systems (ICEMS), 2015 18th International Conference on, Oct, 2015

Proofreading

**Il-Kuen Won** He received the B.S. degree in electrical and electronic engineering from Sungkyunkwan University, Suwon, Korea, in 2013. He is currently working toward the Ph.D. degree in electrical and computer engineering at Sungkyunkwan University, Suwon, Korea. His research interests include inverter, motor control and battery systems.

**Kyoung-min Choo** He received the B.S. degree in Automation System from Dongyang Mirae University, Seoul, Korea, in 2014. He is currently working toward the Ph.D. degree in electrical and computer engineering at Sungkyunkwan University, Suwon, Korea. His research interests include control of power converters and motor-drivers.

**Soon-Ryung Lee** He received the B.S. degree in electrical engineering from Chungang University, Seoul, Korea, in 2013. He is currently working toward the Ph.D. degree in electronic engineering at Sungkyunkwan University, Suwon, Korea. His research interests include dc/dc converters, battery charger systems, and power supplies.

**Jung-Hyo Lee** He received the B.S. degree in electrical engineering from Konkuk University, Seoul, Korea, in 2006, and the M.S. and the Ph.D. degrees in electrical engineering from Sungkyunkwan University, Suwon, Korea, in 2008 and 2013, respectively. From 2013 to 2016, he was a senior researcher of automotive component R&D Team in LG Innotek. From 2016, he has been an assistant professor in Kunsan National University, Gunsan, Korea. His research interests include converters and inverters for motor drive application.

**Chung-Yuen Won** He received B.S. degree in electrical Engineering from Sungkyunkwan University, Suwon, Korea, in 1978, and the M.S. and Ph.D. degrees in Electrical Engineering from Seoul National University, Seoul, Korea, in 1980 and 1987, respectively. From 1990 to 1991, he was with the Department of Electrical Engineering, University of Tennessee, Knoxville, TN, USA as a Visiting Professor. Since 1988, he has been with a member of the faculty of Sungkyunkwan University, where he is a Professor in the College of Information and Communication Engineering; also, in 2008-2013, he was the director of Samsung Energy Power Research Center. He was the President of the Korean Institute of Power Electronics in 2010. Since 2016, he has been a director of the DC distribution research center. His current research interests include the power electronic of electric machines, electric / hybrid vehicle drives, power converters for renewable energy systems. He is a member of the Korea Institute of Power Electronics.

Proofreading