BESS life span evaluation in terms of battery wear through operation examples of BESS for frequency Regulation

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Abstract— **Recently the application of frequency control using Battery Energy Storage System(BESS) has gained research interest due to the benefits of BESS. As such electric companies such as Korea Electric Power Corporation(KEPCO) has adopted this in their operation schemes. Most researches pertaining battery life assessment techniques do not take into account factors that cause deterioration. In this paper, we estimate battery life from the viewpoint of capacity through operational data of BESS for Frequency Regulation(FR). Also, the lifetime of the BESS is evaluated considering wear. The wear cost of each operation mode is derived by introducing a Wear Density Function reflecting factors of C-rate, temperature, and DOD.**

Index Terms— **Battery wear, Battery management system, Energy Storage system, Frequency regulation, State of health,**

NOMENCLATURE

DOD	depth-of-discharge of the battery
ACC	achievable cycle count at a specific DOD
AWC	average wear cost calculated from the battery price and the DOD-ACC curve
WDF	wear-density-function,
μ	cycle efficiency of the battery (average value for charge and discharge)
q	amount of battery energy
s	state of the charge of the battery

I. INTRODUCTION

There has been a paradigm shift from supply to demand-driven policy in recent times, KEPCO (Korea Electric Power Corporation) is in the progress of creating new business strategies to meet the change in energy policy of government as well as discovering new businesses through reduction of demand power via new technologies due to ICT convergence. Among these are the use of Frequency Regulation by utilizing BESS. The company implemented 52MW of BESS power in 2014, 236MW in 2016 and currently has a goal of increasing the installed capacity to 500MW by the end of 2017.

Most researchers in the area BESS for Frequency regulation consider the analysis of objective function that is based on economic effects of appropriate capacity and frequency control method [1]. Normally the operational life of BESS is referenced from the battery manufacturer's condition specific data sheet, while SOH can be deduced via the guaranteed BESS capacity. This method is flawed since it has a very low accuracy. Battery wear occurs as a result of repeated charging and discharging. Battery degradation does only lowers the rated capacity, but also raises internal resistance, low voltage, and self-discharge [2]. The main factors that cause aging are temperature change, over-charge, over-discharge, C-rate, DOD and so on [3] [4].

Existing SOH estimation methods include electrical modeling and electrochemical modeling. In the case of the electrical modeling method, a rest time of the battery is needed to ensure accurate measurement, also a stable measurement environment is required. Due to the influence of environmental factors such as temperature, it is difficult to perform real-time measurement in the field and it involves large errors. High-precision sensors and analyzers are also required for real-time measurements. In the case of electrochemical models, the estimation accuracy is excellent, but it is time-consuming, costly and difficult to estimate the parameter in real-time. Also, both of these methods require that the model parameters be reset for each battery under investigation, thus the experiment has to be repeated. To overcome this drawback, we propose a Wear Density Function that can calculate the wear cost for each SOC.

The Wear Density Function derived from the standardized cycle life test method (ACC-DOD) is used in this paper [5]. This enables practical and accurate system level SOH estimation from the user's perspective. Furthermore, the actual operation data of BESS for 24MW-6MWh FR operated by KEPCO is used to predict the BESS service life. Two methods of estimating battery life expectancy are proposed, one based on energy consumption and the other is life expectancy through

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deterioration of density function considering C-rate, temperature, and DOD. These main factors of battery deterioration, are derived.

II. SOH ESTIMATION MODEL FROM THE SYSTEM LEVEL PERSPECTIVE

A. Derivation of Wear Denstiy Function (WDF)

The life cycle is reduced in high DOD operation thus life cycle tendency according to the charge / discharge depth and the EOL (End of life) is mostly influenced by DOD.

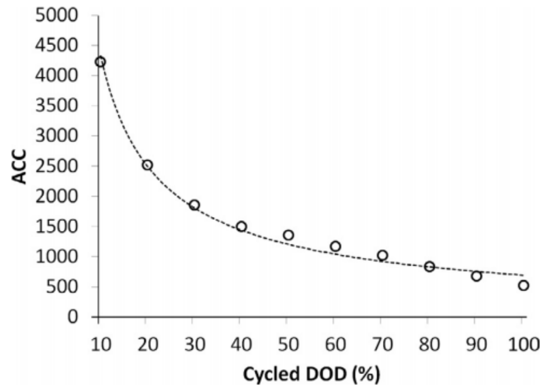

Figure 1. A lithium-ion DOD-ACC cycle life Model [6]

However, accurate life cycle prediction for complex usage patterns is difficult to provide. For example, Figure 1 shows the life cycle data of a lithium-ion cell measured at 10% increments of DOD and provides information about how many cycles can be used. Since the input and output amounts of energy of one cycle are different for each DOD, simple comparison like the above data above cannot be applied. For a quantitative comparison, it is necessary to determine how much battery degradation is related to input / output energy per unit energy. Therefore, in this study, the battery degradation according to the DOD can be calculated by the following equation using the concept of the Average Wear Cost (AWC) [5].

$$\begin{aligned}&\text{Average Wear Cost(DOD)}\\&=\frac{Battery\ Price}{Total\ Transferrable\ Enerygy\ during\ the\ cycle}\\&=\frac{Battery\ Price}{ACC(D)\times 2\times DOD\times Battery\ Size\times Efficient}\end{aligned}\qquad(1)$$

For example, if the battery DOD is 40%, the ACC (Achievable Cycle Count) is 1,500, the battery price is $ 10,000, the capacity is 16 kWh, and the charge / discharge efficiency is 0.9, (1) produces $ 0.64/kWh. That is, when the battery is repeatedly charged and discharged with a DOD of 40%, the wear cost is about $ 0.64 per kWh. In this case, the wear cost corresponds to only the case where charging / discharging is complete at 40%. On the other hand, it is difficult to evaluate the direct wear cost for a complex cycle pattern where the wear density function representing the wear cost is computed at arbitrary SOC point. The total deterioration cost and the remaining service life SOH can be obtained by integrating the wear cost with respect to the wear density function.

The degradation cost function for the unit input / output energy is defined as $W_d(S)$. Where S is the SOC interval (S+ △S). The Average Wear Cost(DOD) formula defined in (1) is expressed as Battery Price, as shown in (2).

$$Battery\ Price = 2\times ACC(D)\times\sum_{s=1-D}^{1-\Delta s}\left(W_d(s)\times\Delta q\right)\qquad(2)$$

Δq is the amount of battery energy during the △S section. For example, if ΔS is set to 10% and DOD is set to 40% and (2) is resolved into (3).

$$\begin{aligned}&Battery\ Price =\\&2\times ACC(0.4)\times\{[W_d(0.6)+W_d(0.7)+W_d(0.8)+W_d(0.9)]\\&\qquad\times 0.1\times Battery\ size\}\end{aligned}\qquad(3)$$

AWC (0.4) is the average wear cost per unit input / output energy of 100% ~ 60% of SOC, which can be obtained from (1). When ΔS is set to 10%, the wear cost of SOC 60% ~70% is $W_d(0.6)$, and SOC 70 ~ 80% is $W_d(0.7)$.

Therefore, it can be expressed as

$$\mathrm{AWC}(0.4) = W_d(0.6) + W_d(0.7) + W_d(0.8) + W_d(0.9)\qquad(4)$$

The SOC interval (ΔS) can be set to 10%, and all intervals of the DOD can be arranged as follows.

$$\begin{aligned}W_d(0.9) &= \frac{Battery\ Price}{ACC(0.1)\times 2\times 0.1\times Battery\ Size\times\mu^2}\\W_d(0.8)+W_d(0.9) &= \frac{Battery\ Price}{ACC(0.2)\times 2\times 0.1\times Battery\ Size\times\mu^2}\\&\vdots\\W_d(0)+\cdots+W_d(0.9) &= \frac{Battery\ Price}{ACC(1)\times 2\times 0.1\times Battery\ Size\times\mu^2}\end{aligned}\qquad(5)$$

Since there are 10 unknowns ($W_d(0)$,⋯ $W_d(0.9)$) and AWC equations according to DOD, there are 10 cases, so all 10 wear density functions according to each SOC can be obtained by the following equations.

$$\begin{bmatrix}1&0&\cdots&\cdots&0\\1&1&0&\cdots&0\\\cdots&\cdots&\cdots&\cdots&\cdots\\1&1&1&\cdots&1\end{bmatrix}\begin{bmatrix}W_d(0.9)\\W_d(0.8)\\\cdots\\W_d(0)\end{bmatrix}=\begin{bmatrix}\dfrac{Battery\ Price}{ACC(0.1)\times 2\times 0.1\times Battery\ Size\times\ \mu^2}\\\dfrac{Battery\ Price}{ACC(0.2)\times 2\times 0.1\times Battery\ Size\times\ \mu^2}\\\cdots\\\dfrac{Battery\ Price}{ACC(1)\times 2\times 0.1\times Battery\ Size\times\ \mu^2}\end{bmatrix}\qquad(6)$$

After obtaining the wear density function $W_d(s)$ for each SOC, $W_d(s)$ at each SOC point is multiplied by the input / output energy of that SOC trajectory.

The total wear cost of the SOC trajectory can be obtained by summing the wear costs for all the SOC sections.

III. LIFE EXPECTANCY BASED ON ENERGY USAGE

We analyzed three cases, steady state, transient state, and ordering condition by considering wear factor using actual data of ‘Substation A’ operated by BESS for frequency regulation of 24MW class. The frequency regulation control algorithm of BESS is classified into steady state and transient state control according to the frequency state [1]. If the system frequency deviates from the frequency dead band (59.97 ~ 60.03 Hz), the frequency regulation control by the speed adjustment ratio is performed. The transient state control determines the target output and discharges when the system frequency exceeds the frequency dead band and meets the transient state judgment criterion. After the transient state is completed, the steady state switching control based on the speed adjustment ratio is performed to recover from the deviation.

In this case study, life expectancy in terms of energy usage and life expectancy using battery Wear Density Function are

A. Transient State

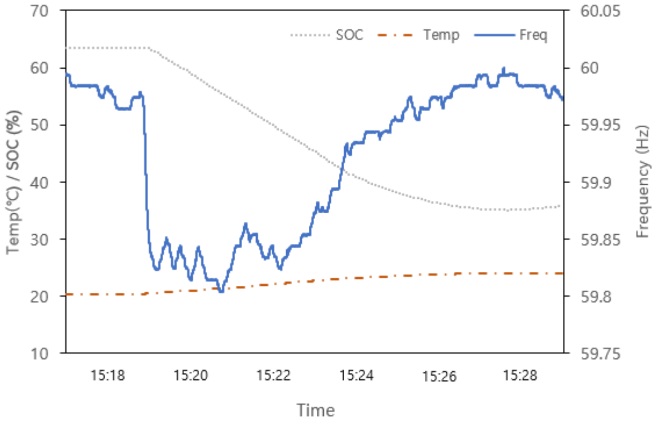

Fig. 2 Simulated transient-state operation of BESS on the grid

Figure 2 is the actual data of the transient state of the substation operated by KEPCO with 24MW-6MWh BESS for Frequency Regulation. It is a graph that the transient state occurring when the frequency drops to 59.8Hz due to the phenomenon such as the dropout of the generator operates at 59.97Hz, BESS reacts to recover the drop-in frequency. A 4C discharge reduced SOC from 65% to 35%. This causes a decrease in SOC. Afterward BESS is charged at 0.2C ~ 0.4C to recover at 65%, causes SOC to return to the normal range after 1 hour. From the graph, the temperature rises by about 5 ° C compared to the normal state at 24.9 ° C. At this point, the input / output energy per batter bank is about 365.186 kWh. The input / output energy per MWh is 575.1 MWh, while the plant capacity per batter bank of A substation is 635kWh.

Transient state conditions in the Korean power system occur four to five times annually on average, according to 'system failure and frequency performance trend for four years (2012 ~ 2015)’. Assuming that, the annual transient input and output energy is given by:

$$Annual\ total\ Energy_{Trasient-state} = \frac{575.1kWh}{1h} \times 5\text{h} \cong \frac{2.875\text{MWh}}{\text{year}} \tag{7}$$

Therefore, the transient state has an input / output energy of about 2.875MWh per year.

B. Steady State

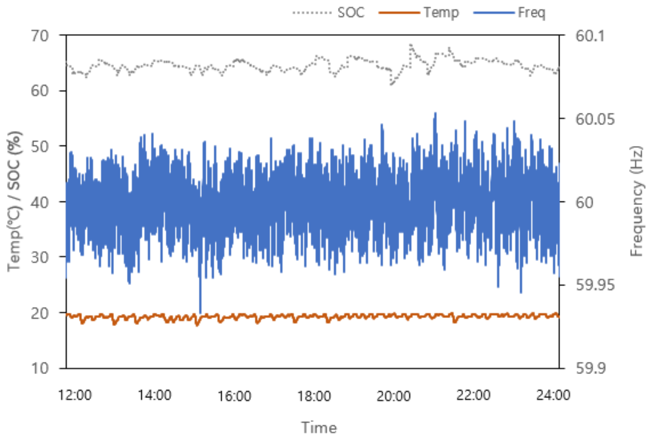

Fig. 3 Actual Steady-state operation of BESS on the grid

The steady state is the operation when the grid frequency is maintained at 60 ± 0.028 Hz. The operating algorithm maintains SOC at 65%. The temperature is 20 ° C and the C-rate is within 0.2 ° C. The daily charge and discharge capacity of a substation in steady state is 16,658 kWh. The total installed capacity of substation A is 7,620kWh, and the input / output energy per day MWh is 2,186kWh. In steady state, the annual total energy is calculated according to (7), except for the transient state operating times (5 hours).

The steady state has an input and output energy of about 797.434 MWh per year.

$$Annual\ total\ Energy_{staedy-state} = \frac{2{,}186kWh}{day} \times \left(364 + \frac{19}{24}\right) \cong \frac{797.434\text{MWh}}{\text{year}} \tag{8}$$

C. Life expectancy in terms of input and output energy

The total annual input and output energy of steady state and transient state is 797.434MWh + 2.875MWh = 800.2MWh / year. Substation A’s BESS battery is guaranteed to be 80% DoD, at 0.5C, and 4000 cycles. The total available input / output energy per 1MWh of battery life is evaluated as follows.

$$Total\ availiable\ energy\ per\ 1MWh\ of\ battery = 1MWh \times 0.8(DOD) \times 2(charge, discharge) \times 4000Cycle \times 0.9^2 = 5{,}184MWh \tag{9}$$

By dividing the actual annual total input / output energy based on the guaranteed input / output energy per 1MWh of

TABLE I. WEAR COST RESULT BY OPERATING MODE TABLE TYPE STYLES

	Steady state (0.2C)	Transient state (0.2C, 4C)	* Combined cycle (Steady state+Transient state)	battery guarantee condition
Wear Cost per cycle	$30.47 / 87.72kWh	$358.26 / 365.2kWh	-	453.6 / 1,01kWh
Number of cycles per year	8,403	5	-	-
Wear cost per kWh	$0.35 / kWh	$0.98 / kWh	$0.36 / kWh	$0.45 / kWh
Annual wear cost	$ 277,062	$ 281.92	$ 279,881	-

battery, the battery life time can be derived from the viewpoint of input / output energy usage. Life expectancy for 5,184 MWh / 800.2 MWh / year = 6.47 years.

We have examined the life expectancy in terms of input and output energy, and the next section looks at the life expectancy based on the actual Wear Density Function.

IV. DERIVATION OF LIFE EXPECTANCY USING THE WEAR DENSITY FUNCTION

The actual wear cost was derived by applying the Wear Density Function through operation data of 'Substation A' with 6MW-24MWh BESS for frequency regulation. Three different cases were analyzed by applying steady state, transient state, and battery guarantee condition.

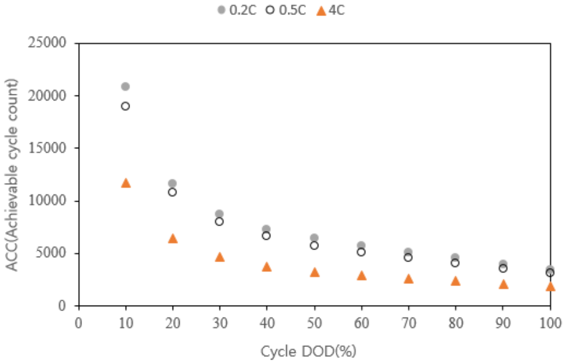

Fig. 4 ACC vs DOD at 25 ° C,

To evaluate the Wear Density Function, ACC data for each DOD at room temperature in Figure 4 was generated from the standard life data provided by Battery Company to follow the tendency of general lithium ion battery via the DOD-ACC graph. The Wear Density Function was derived from equation (5) according to C-rate, temperature, and SOC. The BESS costs was $ 5.5 million with a battery capacity of 125 MWh.

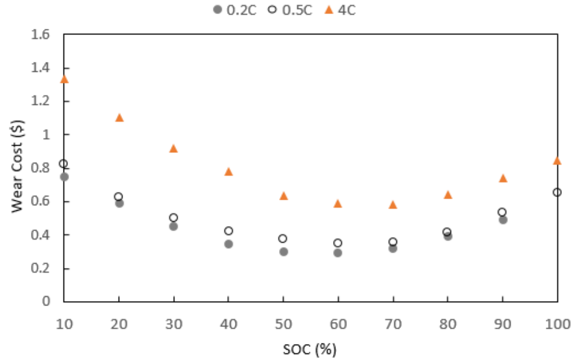

Fig. 5 Wear cost for a 125MW h, $5.5 million battery obtained using the DOD-ACC curve in Fig.4

Figure 5 is a graph showing wear costs at 0.2C, 0.5C, and 1C at 25 ° C. Operation at a higher C-rate, 4C shows a highest wear cost for each SOC.

A. *Expected wear cost and life expectancy for each operation mode*

A cycle pattern for each operation mode of steady state operation and transient state operation was generated through actual BESS operation for FR. Each graph shows the SOC per second and the input and output energy of the battery at that time.

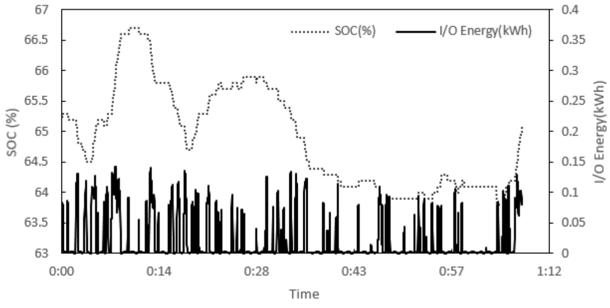

Fig.6 Cycle pattern at steady state

Figure 6 shows the steady-state data for one hour extracted from the actual BESS operation for FR. The applied frequency regulation algorithm adjusts SOC to maintain 65% in steady state. The input and output energy (kW / h) according to the change of SOC per second is shown. The extracted steady-state data constitute one cycle with the initial SOC and end SOC being equal.

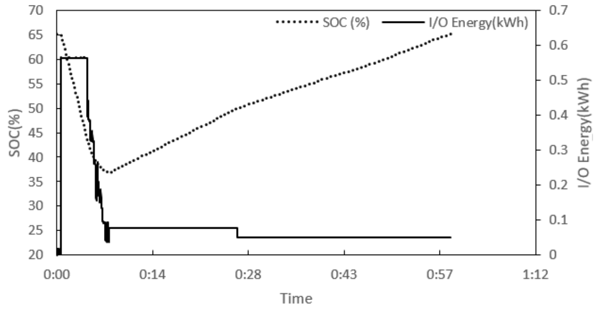

Fig. 7 Cycle pattern at transient state

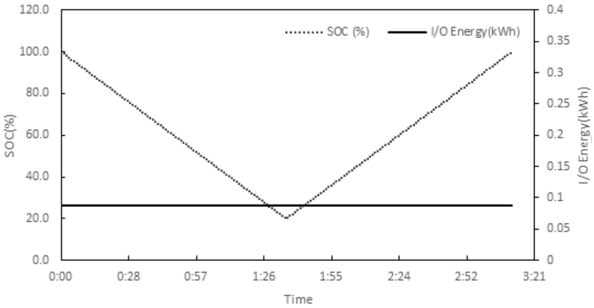

Fig. 8 Cycle pattern at battery guarantee condition.

Figure 7 shows the transient state. Here the BESS is discharged at 4C for 5 minutes to recover the frequency due to the dropout of the generator. The BESS is then charged to 65% at 0.2 C to recover to the steady state.

Result from Figure 8 is obtained from manufacturer's data on the battery life cycle. BESS application for FR guarantees 4000 cycles under 80% DOD at 0.5C under room temperature condition. Thus, the guaranteed conditions determine the energy capacity of the battery up to the EOL.

The cycle of each operation mode has the same SOC at the beginning and end, and the Wear cost is shown in Table 1 according to each condition. *Wear cost per cycle* represents the input / output energy and the wear cost at that time for one cycle of each condition. *Number of Cycles per year* indicates the number of cycles per year under operation conditions. In the case of transient state analysis, the number of cycles for a year was recorded as 5 and the steady state analysis operated at 8403 cycles. *Wear Cost per kWh* is converted into kWh per unit of wear cost per cycle.

From the above section, the life expectancy can be derived via (10).

$$\begin{aligned}&Life\ expectancy\ of\ ESS\ for\ FR\\&=\frac{ESS\ total\ wear\ cost}{Annual\ wear\ cost\ in\ FR\ operation}\\&=\frac{\$0.45/kWh\times 5{,}184{,}000kWh}{(\$0.35/kWh\times 797{,}434kW+\$0.98/kWh\times 2{,}875kWh}\\&=8.31\text{ year}\end{aligned}\tag{10}$$

Dividing the total wear cost of the BESS battery life by the annual wear cost can lead to an expected life. Life expectancy is expected to be 8.31 years.

V. CONCLUSION

The accurate estimation of an expected batter life time serves as significant factor to build BESS for Frequency regulation. Since expected life time is dependent on the capacity of the BESS and the operational algorithm, the accurate estimation of expected life time is very important. The SOH estimation so far has been estimated by using methods such as OCV (Open circuit voltage) and DC-IR (Direct current -Internal resistance), or by simply dividing the usage capacity by the total capacity. However, these methods differ in accuracy depending on temperature, C-rate, and SOC. In addition, the lifetime evaluation was performed by using two methods with BESS data for frequency regulation obtained from an actual operation. The battery life obtained via the simple method was 6.47 years. The battery life expectancy derived from the Wear Density Function is 8.31 years. Since our proposed wear density function method takes into consideration temperature, C-rate, and DOD it achieves a much accurate expected life time.

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