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Modeling of Battery for EV using EMTP/ATPDraw

Jun-Hyeok Kim*, Soon-Jeong Lee*, Eung-Sang Kim, Seul-Ki Kim**, Chul-Hwan Kim† and László Prikler*****

Abstract – As environmentally friendly energy takes center stage, interests for Electric Vehicles/Plug in Hybrid Electric Vehicles (EVs/PHEVs) are getting increase. With this trend, there is no doubt EVs will take large portion to penetrations of total cars. Therefore, accurate EV modeling is required. Battery is one of the main components with the power system view of aspect. Hence, in this paper, reviews and discussions of some types of batteries for EV are contained by considering energy density and weight of the batteries. In addition, simulations of Li-Ion battery are accomplished with various variables such as temperature, capacity fading and charge/discharge current. It is confirmed that temperature is the main factor of capacity fading. Validation of the modeled battery is also conducted by comparing it with commercialized battery.

Keywords: Battery, Capacity fade, EMTP/ATPDraw, Charge/discharge current, *SoC*

1. Introduction

These days most of countries and companies focus on eco-friendly growth. With this circumstance, Electric Vehicles (EVs) take center stage. EVs can reduce the amount of consumption of fuel fossil, and thus, it can reduce the amount of CO_2 emission. However, this is not the only reason why the interests about EVs are growing. EVs can operate as distributed generation as well. That is to say, it can operate as power system device for compensating insufficient power or for SMART GRID. For these reasons, therefore, it is clear that EVs will take large portion of total complement of car. In this state of affairs, analyses of effect on distribution system with EVs are essential. And accurate battery modeling should be considered as first priority for the analyses.

Since future studies of this paper are analyzing the effects on grid when EVs are connected, EMTP/ATPDraw which is one of the widely used programs for analyzing transient phenomena is used. However, there is no such battery model in that program. Hence modeling of battery with EMTP/ATPDraw is conducted in this paper.

There are some types of battery modeling, specifically: experimental, circuit-based and mathematical. Experimental modeling and circuit-based modeling cannot estimate State-of-Charge (*SoC*). However, estimations of *SoC* are very important part of battery modeling. Hence, mathematical modeling is used in this paper. This paper is divided into four main parts. In the section 2, brief introductions of batteries are contained. And battery for modeling in this paper is selected based on section 2. In the section 3, theoretical backgrounds of battery modeling are presented. The section 4 contains simulation result of modeled battery with various aspects such as internal resistance, charging/discharging current and capacity fading. And it is verified in section 5. This paper ends with conclusion in the last section.

2. Battery Selection

There are some types of batteries for EV such as Lead-Acid, Lithium-Ion, Nickel-Cadmium and Nickel-Metal-Hydride. To model battery, selection of battery is one of the most crucial factors that have to be considered. Brief characteristics of each type of batteries are indicated in Table 1 [1-5].

However the first priority considering EV is how long EV can drive with the battery. Therefore, weight and energy density of the battery should be considered first. Brief data of weights and costs of batteries are summarized in Table 2 [6].

The more energy the battery has, the more driving distance EV gets. And in the same way, the less weight the

Table 1. Brief characteristics of batteries for EV

	Lead Acid	Ni-Cd	Ni-MH	Li-Ion
Cycle Life	400	500 ~ 1000	400 ~	300 ~
Self discharge	10%	30%	30%	3%
Memory effect	No	Yes	Little	No
Safety	No BMS	Good	Good	Poor
Price	inexpensive	inexpensive	20%	40%
Eco-friendly	No	No	Yes	Yes
Weight	Very heavy	Heavy	Moderat	Light

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† Corresponding Author: Dept. of Electrical and Electronic Engineering, Sungkyunkwan University, Korea. (hmwkim@hanmail.net)
* Dept. of Electrical and Electronic Engineering, Sungkyunkwan University, Korea. (kjh30309@naver.com, kiraoov@gmail.com)
** Korea Electrotechnology Research Institute, Korea. ({eskim, blksheep}@keri. re.kr)
*** Dept. Electric Power Engineering, Budapest University of Technology and Economics, Hungary. (prikler.laszlo@vet.bme.hu)

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Table 2. Weights and costs of batteries those are applicable to electric vehicles

Battery	Weight(Wh/kg)	Cost($/kWh)
Lead-Acid	20 to 30	50 to 80
Nickel-Cadmium	Less than 50	70 to 100
Nickel-Metal-Hydride	Less than 60	800 to 1200
Lithium-Ion	Larger than 100	300 to 600

battery has, the more driving distance EV gets. Hence, the battery which has high energy density and low weight should be contemplated to use for EV. In this respect, Li-Ion batteries are getting the limelight because of its high energy density and relatively low weight as shown in Table 2. Therefore, Li-Ion battery is used in this paper.

3. Battery Modeling

3.1 EMTP/ATPDraw

In this paper EMTP/ATPDraw is used for modeling the battery. The Electromagnetic Transient Program (EMTP) is the tool used to simulate transient electromagnetic (EM) phenomena, and it is one of the most widely used programs throughout electric utilities [7]. And ATPDraw is a graphical, mouse-driven pre-processor to the ATP version of the Electromagnetic Transients Program (EMTP) [8].

MODELS in ATP is a general-purpose description language supported by an extensive set of simulation tools for the representation and study of time-variant systems [8]. The MODELS provides the monitoring and controllability of power system as well as some other algebraic and relational operations for programming. With some compromised functions such as repetition, conditional path selection, and user defined functions, it is also called a new TACS [9].

As stated, there is no doubt that EV will be brought out. However, without analyses for possible effect on power system, it cannot be commercialized. In this paper, EMTP/ATPDraw which has advantages of analyzing transient phenomenon is used. As mentioned, however, there is no battery model with the program. Thus, modeling of battery with the program is indispensable not only analyzing battery itself but also analyzing the effects on grid when EVs are connected.

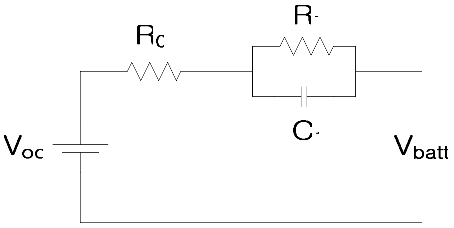

Fig. 1. Thevenin battery model

3.2 Battery models

There are some types of battery modeling such as experimental model, circuit-based model and mathematical model. However, experimental model does not properly describe cell dynamics. Hence, circuit-based model and mathematical model are discussed in this paper [10].

3.2.1 Circuit-based model

Since this method can represent electrical characteristics of battery, circuit-based model can possibly be considered as suitable modeling method. The most commonly used circuit-based battery model is Thevenin battery model as in Fig. 1.

Where,

V_{oc}	Open-circuit voltage (V)
R_0	Internal resistance (Ω)
R_1	Overvoltage resistance (Ω)
C_1	Capacitance of the battery (F)
V_{batt}	Battery voltage (V)

The main disadvantage of this model is all components in this equivalent circuit are assumed to be constant. However, it varies depending on the conditions of battery [11]. Furthermore, circuit-based models including thevenin model do not take account of *SoC*.

3.2.2 Mathematical model

In 1965, Shepherd [12] suggested battery model mathematically, as in (1). It describes electrochemical behavior of the battery directly [13].

$$V_{batt} = E_0 - K\left(\frac{Q}{Q-it}\right)i + A\exp(-B\cdot Q^{-1}\cdot it) - Ri \qquad (1)$$

Where,

E_0	No-load voltage (V)
K	Polarization voltage (V)
Q	Battery capacity (Ah)
A	Exponential zone amplitude (V)
B	Exponential zone time constant inverse $(\text{Ah})^{-1}$
R	Internal resistance (Ω)
it	Actual battery charge (Ah)
i	Battery current (A)
V_{batt}	Output voltage of the battery (V)

However, this model cannot reflect performance of the battery because it assumes internal resistance as constant. As mentioned, it is impossible to describe exact performance of the battery with fixed internal components.

Generic battery model [14] progresses with Shepherd's model, as in (2-3).

$$E = E_0 - K\left(\frac{Q}{Q-it}\right) + A\exp(-B \cdot it) \tag{2}$$

$$V_{batt} = E - R \cdot i \tag{3}$$

In Generic battery model, $K(Q/(Q-it)i$ term in Shepherd's model is replaced with $K(Q/(Q-it)$ to prevent algebraic loop and simulation instability. Nonetheless, this model still assumed internal resistances as constant.

In reality, however, internal resistances are varied depending on the value of *SoC*. On the other hand, in [15] all equations are functions of *SoC*. That makes possible internal resistances have various values according to the value of *SoC*. Therefore, equations below [15] are used, in this paper.

$$\begin{aligned} V_{OC}(SoC) = {} & -1.031 \cdot e^{-35 \cdot SoC} + 3.685 + 0.2156 \cdot SoC \\ & - 0.1178 \cdot SoC^2 + 0.3201 \cdot SoC^3 \end{aligned} \tag{4}$$

$$R_{Series}(SoC) = 0.1562 \cdot e^{-24.37 \cdot SoC} + 0.07446 \tag{5}$$

$$R_{Transient\_S}(SoC) = 0.3208 \cdot e^{-29.14 \cdot SoC} + 0.04669 \tag{6}$$

$$C_{Transient\_S}(SoC) = -752.9 \cdot e^{-13.51 \cdot SoC} + 703.6 \tag{7}$$

$$R_{Transient\_L}(SoC) = 6.603 \cdot e^{-155.2 \cdot SoC} + 0.04984 \tag{8}$$

$$C_{Transient\_L}(SoC) = -6056 \cdot e^{-27.12 \cdot SoC} + 4475 \tag{9}$$

Where,

V_{OC}	Open-Circuit Voltage (V)
$R_{Transient\_S}$, $C_{Transient\_S}$	Short-time constants
$R_{Transient\_L}$, $C_{Transient\_L}$	Long-time constants
R_{Series}	Immediate voltage drop constant

In above Eqs. (4-9), R_{Series} is responsible for immediate voltage drop of the step response. $R_{Transient\_S}$ and $C_{Transient\_S}$ are responsible for short-time constant of the step response. $R_{Transient\_L}$ and $C_{Transient\_L}$ are responsible for long-time constant of the step response [15]. The main advantage of using these equations is the fact that internal resistances can be varied depending on the value of *SoC*.

3.3 Measurement methods for state-of-charge

There are three main methods to measure the *SoC*: voltage measurement method, impedance measurement method and coulomb counting method [16].

Voltage Measurement Method (VMM) is the simplest method to calculate *SoC*. It uses a relationship between output voltage of the battery and *SoC*. However, the relationship can be affected by temperature and charge/discharge rate of the battery. Hence, although it is easy to calculate *SoC*, the result is rather roughly accurate.

Impedance Measurement Method (IMM) uses relationship between internal impedance and *SoC*. As stated above, internal impedance is varied depending on conditions of the battery. And *SoC* is one of those conditions. Thus, if the value of internal impedance is identified, it is easy to calculate the value of *SoC*. However, it is not widely used because of the difficulties to measure internal resistances while the battery is charged or discharged.

Current is used in Coulomb Counting Method (CCM). The unit of the energy in the electric charge is coulombs and that is equal to the integration of overtime-current. Therefore, from this point, the remaining capacity in the battery can be calculated by measuring the current which is flowing into or leaving from the battery. To calculate accurate *SoC* in CCM, self-discharge current and columbic efficiency should be taken into account. But still it is useful and is making acceptably accurate result. So, in this paper, CCM is used with ignoring self-discharge current and columbic efficiency. Calculation of *SoC* using CCM is following (10)~(11).

$$SoC = 1 - \left(\int initial - \int \frac{i}{Q} dt\right) \tag{10}$$

$$\int initial = \left(1 - \frac{SoC_0}{100}\right) Q \tag{11}$$

Where,

Q	Battery capacity (Ah)
i	Battery current (A)
SoC_0	Initial value of *SoC*

3.4 Capacity fading

"Capacity fading" is one of the main characteristics of battery. Capacity fading refers to the phenomenon that usable capacity of the battery decreases due to run-time, temperature and charging/discharging cycle. Generally, it is considered that the battery is available until it has 80% of its initial capacity. Hence, with this, consideration for the effect of capacity fading is important factor in battery modeling [17].

There are three main reasons causing capacity fading which are temperature, time and cycle of the battery. In (12), capacity loss by temperature and time is expressed [18].

$$Q = A\exp\left(\frac{-E_a}{RT}\right)t^z \tag{12}$$

Where,

Q	Capacity loss (%)
A	Pre-exponential factor
E_a	Activation energy (J)
R	Gas constant
T	Temperature (K)
t	Time
z	Exponent of time

Among above parameters, A and E_a are adjustable parameters. In this paper, they were set at 1.1443×10^6, 4.257×10^4 and 0.5 respectively [18, 19].

Capacity fading caused by cycling is indicated in (13) [20, 21].

$$Q_{loss\_cycle} = A \cdot \exp(\frac{-E_a}{RT}) \cdot (I^{PR})^{0.552} \tag{13}$$

Where,

Q_{loss_cycle}	Capacity loss by cycling (%)
I^{PR}	Number of cycle converted by Ah-process

In (13), capacity fading due to cycle is expressed as similar as (12). The number of cycles is converted to Ah-processed (I^{PR}), the integral of absolute value of current over time [21]. Ah-variable represents the amount of charge transported during cycling. Advantage of using Ah-process is allowances for quantifying and correlating the capacity fading behaviors with different C-rates [20].

4. Modeling of the Battery using EMTP/ATPDRAW

4.1 State-of-charge

As stated, CCM is used in this paper. The equations for calculation are following (10)~(11).

In this paper, battery capacity Q is set at 2.3Ah. And it is assumed that the modeled battery has negative current when it is charged, on the other hand, has positive current when it is discharged. According to the equations, *SoC* should have linear characteristic if the battery current set as constant. Therefore, as the battery current increase, the time which *SoC* is reached to 1 will be shorten.

4.2 Internal resistances

As SoC is changed, internal resistances are changed as well. Repeatedly, this characteristic is one of the most important factors. Simulation result of the internal resistances is presented in Table 3 and Fig. 2.

Table 3. Battery internal resistances

SoC	$R_{Series}(\Omega)$	$R_{Transient\_S}(\Omega)$	$R_{Transient\_L}(\Omega)$
0	0.23066	0.36749	6.65284
0.1	0.08811	0.06409	0.04984
0.2	0.07565	0.04763	0.04984
0.3	0.07456	0.04674	0.04984
0.4	0.07446	0.04669	0.04984
0.5	0.07446	0.04669	0.04984
0.6	0.07446	0.04669	0.04984
0.7	0.07446	0.04669	0.04984
0.8	0.07446	0.04669	0.04984
0.9	0.07446	0.04669	0.04984
1	0.07446	0.04669	0.04984

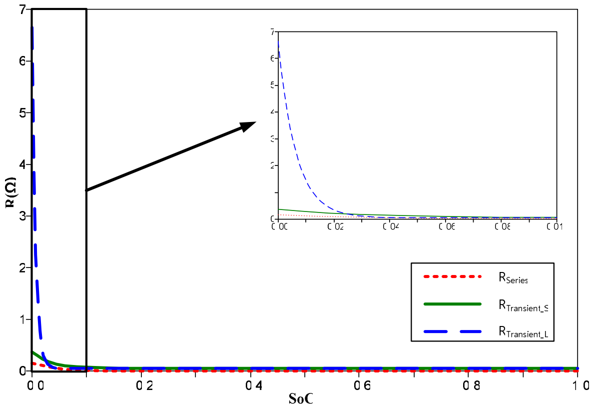

Fig. 2. Simulation result of internal resistances

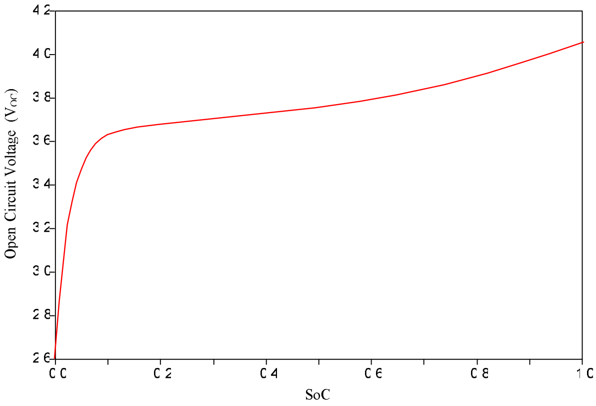

Fig. 3. Simulation result of *Voc* when the battery is charged

As shown in Table 3 and Fig. 2, using (5), (6) and (8), internal resistances can be calculated and it rapidly fluctuates with *SoC* while *SoC* increases from 0 to 0.1. And it is gradually changed until it reaches each of their minimum values. This implies most of power losses are occurred when charging or discharging of the battery begins or ends, respectively.

4.3 Charging characteristics

For charging mode, it is assumed that No-load is connected. This means, in this simulation, only Voc is concerned. Simulation is conducted using (4) and simulation result is shown in Fig. 3.

In this simulation, battery capacity is set at 2.3Ah and charging current is set at 1A as constant value.

Generally, Open-Circuit Voltage Voc sharply changes when charging is started. In other words, when *SoC* is roughly between 0 to 0.2, Voc rapidly changes. And it gradually changes as *SoC* is reached to 1. This tendency is indicated in Fig. 3. It is noticed Voc starts at 2.6V and reaches at 4.1V in Fig. 3. That is to say, cut-off voltage and nominal voltage of modeled battery is 2.6V and 4.1 V, respectively.

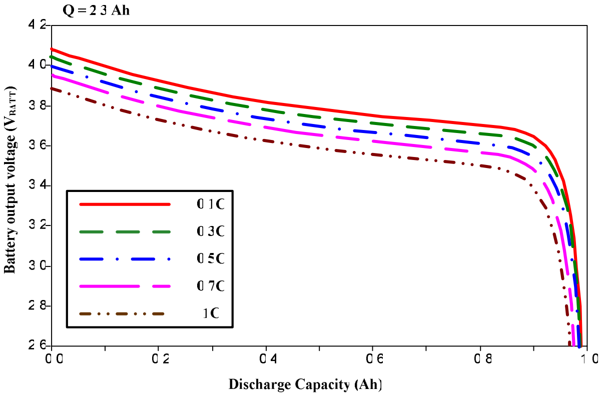

Fig. 4. Simulation result of output voltage of the modeled battery when discharge current caries 0.1C to 1C

4.4 Discharging characteristics

4.4.1 Effect of discharging current

Discharging mode is also following (4-9). The main difference between charging mode and discharging mode is consideration of internal resistances. In discharging mode, it should be taken into account. Theoretically, as discharge current increase, power losses due to internal resistances should be larger. The reason is power loss follows "$P = I^2R$". Simulation results when the discharging current varies are presented in Fig. 4.

In Fig. 4, C means the discharge current which can make battery fully discharged in 1 hour. As expected, power consumed by internal resistances is grown as discharge current increase.

4.4.2 Capacity fading

Effect of capacity fading can be analyzed by (12) which is based on Arrhenius equation. In this simulation, irreversible capacity loss according to time is analyzed with three different temperatures.

Theoretically, as temperature higher, chemical reactions in battery are become faster. For this reason, the performance of battery can provide better performance, however, at the same time, it causes extra power loss. In other words, high temperature causes reduction of the battery life. As a rule of thumb, reaction rate of the battery is become doubles as the temperature of battery increase 10 ˚C. For instance, if specific battery can be used in an hour at 30˚C, it can be used in two hours at 20˚C.

Time is also one of the main factors causing capacity fading. As mentioned previously, battery makes output voltage using chemical reaction. However, although users do not use the battery, it does not mean its chemical reactions stop either. Thus, as time goes by, the battery life is kept reducing.

For the reasons above, it is expected that life reduction or capacity loss of the battery becomes larger as temperature and time increase.

Table 4. Power loss due to time and temperature

Time (day)	Power loss (%)		
	5˚C	25˚C	45˚C
1000	0.36	1.26	3.70
2000	0.51	1.78	5.24
3000	0.63	2.18	6.42
4000	0.73	2.52	7.41
5000	0.81	2.81	8.29
6000	0.89	3.08	9.08
7000	0.96	3.33	9.81
8000	1.03	3.56	10.49
9000	1.09	3.78	11.12
10000	1.15	3.98	11.72
11000	1.21	4.17	12.30
12000	1.26	4.36	12.84
13000	1.32	4.54	13.37
14000	1.37	4.71	13.87
15000	1.41	4.88	14.36

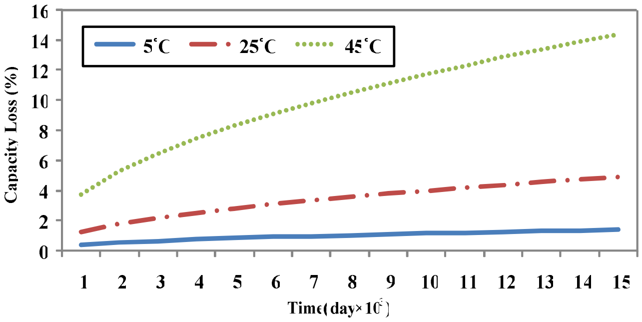

Fig. 5. Simulation results of capacity loss versus time

As shown in Table 4 and Fig. 5, power loss due to time and temperature gets worse as the time and temperature increase. In addition, it is noticed that higher temperature causes severely more power loss in much shorter time than those of lower temperatures. At 15000 days, for example, 1.41 percent of power losses are occurred at 5˚C, however 4.88 and 14.36 percent of power losses are occurred at 25 ˚C and 45 ˚C, respectively. This simulation result verifies theoretical expectation, as stated above.

As charging/discharging repeated, irreversible capacity loss is occurred as well and it is called "cycling fading". Simulation results of capacity loss due to cycling are presented in Table 5 and Fig. 6.

In this simulation, 1C is used and it is shown that capacity losses by cycling are significantly worse when it is conducted in high temperature. Percentage capacity loss is 1.537% at 5˚C. On the other hand, it causes 15.552% of capacity loss at 45˚C.

Capacity fading by temperature, time and cycle, by the way, cannot be separated. Therefore, it should be considered at once. Simulation results considering those three variables are shown in Fig. 7.

This simulation is conducted with 25˚C and 45˚C, and assumed charging/discharging cycle is implemented one time per day. As shown in Fig. 7, it causes about 14 and 41

Table 5. Power loss due to cycle number and temperature

Cycle number	Capacity loss (%)		
	5˚C	25˚C	45˚C
1	0.028	0.096	0.285
100	0.358	1.231	3.623
200	0.525	1.804	5.312
300	0.656	2.257	6.645
400	0.769	2.646	7.788
500	0.870	2.993	8.809
600	0.962	3.309	9.742
700	1.048	3.603	10.607
800	1.128	3.879	11.419
900	1.204	4.140	12.186
1000	1.276	4.388	12.915

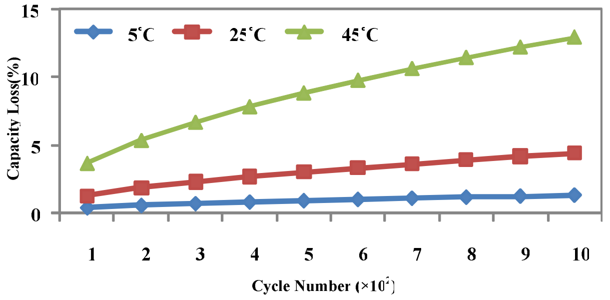

Fig. 6. Simulation results of capacity loss due to charging/ discharging cycle (conducted with 1C)

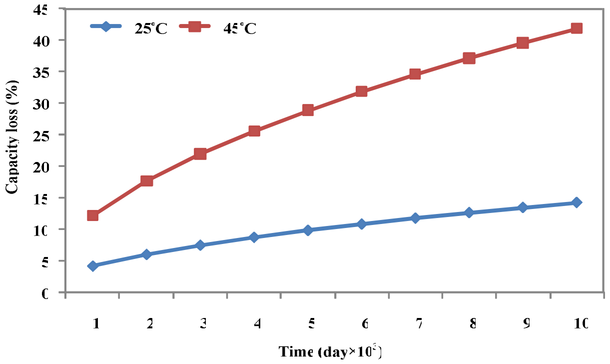

Fig. 7. Simulation results of total capacity loss (25˚C and 45˚C)

percent of power loss at 25˚C and 45˚C, respectively. It suggests that temperature is the most crucial factor affect power loss of the battery.

5. Validation of Modeled Battery

Comparisons between modeled battery and commercialized battery "ANR26650" are presented in Fig. 8 ~ Fig. 10. In these comparisons, capacity of modeled battery Q is set at 2.3Ah and discharge current is provided sequentially.

Owing to the difference in open-circuit voltage, modelled battery and ANR26650 have not exactly same result, however, those two batteries have considerably similar pattern, as shown in Fig. 8. And analogousness of capacity loss by cycling is also shown in Fig. 9 and Fig. 10.

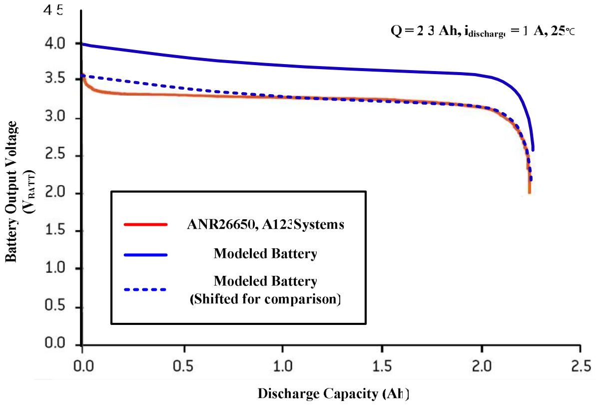

Fig. 8. Comparison of battery output voltage in modeled battery and commercialized battery at 25˚C

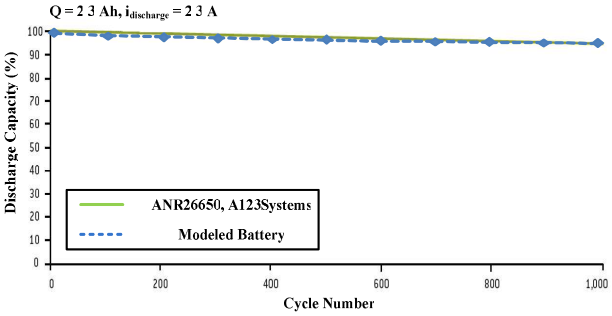

Fig. 9. Comparison of capacity loss by cycling in modeled battery and commercialized battery at 25˚C

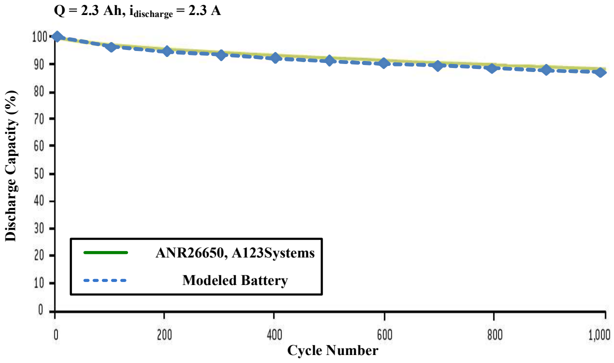

Fig. 10. Comparison of battery output voltage in modeled battery and commercialized battery at 45˚C

6. Conclusion

Since the battery for EV should have high energy density and low weight, Li-Ion battery is chosen for this paper. And mathematical battery model is used because of some explained disadvantages of circuit-based model and experimental model. It is introduced that the three main factors for battery modeling are *SoC*, internal resistances and capacity fading. With mathematical modeling, *SoC* and varying internal resistances are taken into account. And it is shown that capacity fading can be caused by temperature, time and cycling. The higher temperature batteries have the more power losses it gets. Likewise, the longer time and larger cycle numbers cause more power losses on battery. Therefore, it can lead reduction of battery life as presented in simulated results. Especially, it is shown that temperature is the most crucial factor among stated variables.

Validation of modeled battery is presented by comparing commercialized battery (ANR26650) and modeled battery. Simulation results verify its validity.

Without sufficient researches of possible effect caused by connected EVs in power system, it is impossible to employ EV technologies. Especially, transient phenomena on power system are more likely to be affected by EVs. Therefore, for analyzing battery characteristics and the effects on grid when EVs are connected are mainly discussed. To be specific, EMTP/ATPDraw which is one of the most appropriate programs for analyzing transient phenomena and simulations on power systems is used for that.

However, despite its advantages in analyzing power system such as transient phenomena, EMTP/ATPDraw does not have any battery models. Hence, modeling battery using EMTP/ATPDraw is worth conducting. So with verified battery in this paper, it is expected that the effects on grid when EVs are connected will be researched for further studies.

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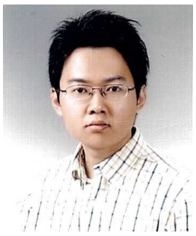

Jun-Hyeok Kim He received B.S degree in School of Electrical and Computer Engineering from Sungkyunkwan University, 2011. At present, he is working on his MS course. His research interests include power system transients, protection and stability with electric vehicle.

Soon-Jeong Lee He received his B.S. degree in Department of Electrical and Electronics Engineering from Kangwon National University, 2010 and M.S. dgree in College of Information and Communication from Sungkyunkwan University, South Korea, 2012 respectively. At present, he is working for his Ph. D. course in Sungkyunkwan University. His research interests are power quality, power system transient analysis, power system protection and electric vehicle.

Eung-Sang Kim He received B.S degree in and M.S degrees in Electrical Engineering from Seoul National University of Science & Technology, 1988. He received his M.S and Ph.D degree in Electrical Engineering from Soongsil University, 1991, 1997 respectively. At present, he is working at KERI. His research interests include modeling and analyzing of distributed generation system, design, control and analysis of micro-grid system.

Seul-Ki Kim He received B.S and M.S degrees in Electrical and Electronics Engineering from Korea University, 1998, 2000 respectively. He received his Ph.D degree in Electrical and Electronics Engineering from Korea University, 2010. At present, he is working at KERI. His research interests include modeling and analyzing of distributed generation system, design, control and analysis of micro-grid system.

Chul-Hwan Kim He received his B.S. and M.S. degrees in Electrical Engineering from Sungkyunkwan University, South Korea, 1982 and 1984, respecttively. He received a Ph.D. degree in Electrical Engineering from Sungkyunkwan University in 1990. In 1990 he joined Cheju National University, Cheju, South Korea, as a full-time Lecturer. He has been a visiting academic at the University of BATH, UK, in 1996, 1998, and 1999. Since March 1992, he has been a professor in the College of Information and Communication, Sungkyunkwan University, South Korea. His research interests include power system protection, artificial intelligence application for protection and control, the modelling/ protection of underground cable and EMTP software.

László Prikler He was born in Mosonmagyaróvár, Hungary on March 7, 1962. He received the M.S degree in Electrical Engineering from the Technical University of Budapest in 1986. His main research interest is computer simulation of power system transients. In parallel with his academic carrier he is working for as consultant and managing director of Systran Engineering. Services Ltd. Mr. Prikler is a Member of IEEE Power Engineering SoCiety and the Hungarian Electrotechnical AsSoCiation. Mr. Prikler was awarded by the Chapter Regional Outstanding Engineer Award by IEEE Region 8 in 2000.