HIGH PRECISION SIMULATION MODEL OF BATTERY CHARACTERISTICS

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This paper reports a simulation model of battery characteristics and its simulation/verification test results. Battery simulation model is necessary in order to simulate systems including batteries such as the grid-connected photovoltaic systems that less depends on the utility grid. The authors created the battery simulation model based on a new method. In this model, internal resistances depend on current, state of charge, and temperature. Verification test results show 0.5 % of power simulation error ratio, high precision was confirmed.

Keywords: AE-PV system, grid-connected PV, battery simulation, battery modeling

INTRODUCTION

Most of the photovoltaic (PV) systems for residences spreading rapidly are grid-connected type. Usually, since this system has no electricity storage, the difference between generated and used electric power is processed by electric power flow of the utility grid. In the future so that the PV systems may spread further, it is necessary to develop “Autonomy-Enhanced” PV (AE-PV) system technologies with electricity storage functions that less depends on the utility grid [1]. To design and evaluate the PV systems with battery storages shown in **Fig.1**, the battery simulation model is necessary [2].

A lot of battery models have been researched. The authors also have been researching it [3] [4]. This time, the authors propose high precision simulation model of battery characteristics.

MODELING

Model

Fig.2 shows the equivalent circuit of the battery model of proposal. Terminal voltage V is estimated by the following equation.

$$V = E - V_d + V_g \quad (1)$$

E is the electromotive force of appearance during charge or discharge. V_d is the voltage drop by current, and consists of resistance component and voltage saturation component. V_g is the voltage rise at final phase of charging, and has a characteristic that looks like the parallel connection of voltage saturation component and current saturation component.

These voltages depend on I, SOC, and T_{25}. I is the current. SOC is the state of charge, and means full charge when SOC = 1. T_{25} is the battery temperature based on 25 deg C.

E is calculated by the following equation which considers the Nernst equation.

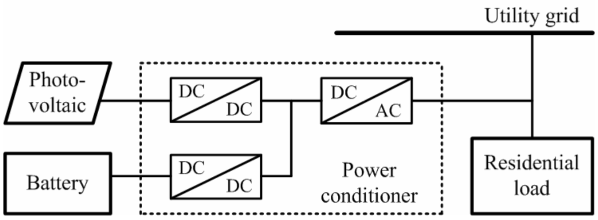

Fig.1: PV system configuration

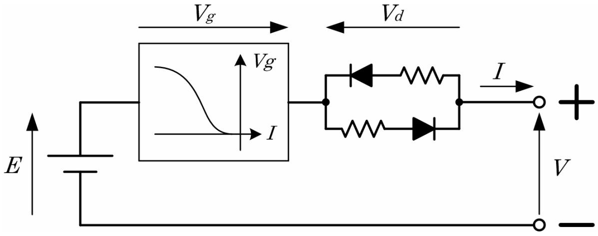

Fig.2: Equivalent circuit of battery

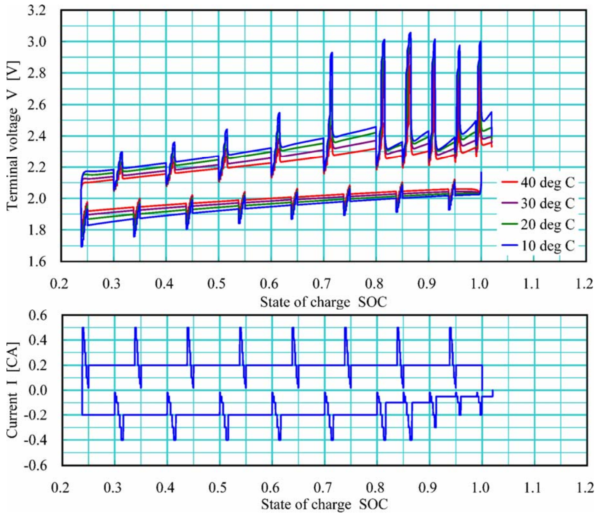

Fig.3: Measured characteristic of test battery

$$E = E_0 + E_1 \ln\left(1 - \frac{1-SOC}{S_E}\right) \tag{2}$$

V_d is calculated by the following equation.

$$V_d = R\,I + V_a\left(1 - e^{-\frac{|I|}{I_a}}\right) \tag{3}$$

During discharge, **R**, **V_a**, and **V_g** are calculated by the following equations.

Case $(I \geq 0)$

$$R = R_0 + R_1 e^{-\frac{SOC}{S_R}} \tag{4}$$

$$V_a = V_{a0} + V_{a1} e^{-\frac{1-SOC}{S_a}} \tag{5}$$

$$V_g = 0 \tag{6}$$

During charge, **R**, **V_a**, and **V_g** are calculated by the following equations.

Case $(I < 0,\ SOC < S_b)$

$$R = R_0 + R_1 e^{-\frac{1-SOC}{S_R}} \tag{7}$$

$$V_a = V_{a0} + V_{a1} SOC \tag{8}$$

$$V_g = V_{ga} e^{\frac{SOC-S_b}{S_g}} \tag{9}$$

Case $(I < 0,\ SOC \geq S_b)$

$$R = R_0 + R_1 e^{-\frac{1-S_b}{S_R}} \tag{10}$$

$$V_a = V_{a0} + V_{a1} S_b \tag{11}$$

$$V_g = V_{ga}\left(2 - e^{\frac{S_b-SOC}{S_g}}\right) \tag{12}$$

$$S_b = S_{b0} - \beta_b |I| \tag{13}$$

$$S_g = S_{g0} + \beta_g |I| \tag{14}$$

Constants described above are calculated by the following equations.

$$E_0 = E_{00}\left(1 + \alpha_{E_0} T_{25}\right) \tag{15}$$

$$E_1 = E_{10}\left(1 + \alpha_{E_1} T_{25}\right) \tag{16}$$

$$S_E = S_{E0}\left(1 + \alpha_{S_E} T_{25}\right) \tag{17}$$

$$R_0 = R_{00}\left(1 + \alpha_{R_0} T_{25}\right) \tag{18}$$

$$R_1 = R_{10}\left(1 + \alpha_{R_1} T_{25}\right) \tag{19}$$

$$V_{a0} = V_{a00}\left(1 + \alpha_{V_{a0}} T_{25}\right) \tag{20}$$

$$S_{b0} = S_{b00}\left(1 + \alpha_{S_{b0}} T_{25}\right) \tag{21}$$

$$\beta_b = \beta_{b0}\left(1 + \alpha_{\beta_b} T_{25}\right) \tag{22}$$

$$S_{g0} = S_{g00}\left(1 + \alpha_{S_{g0}} T_{25}\right) \tag{23}$$

Table 1 shows these symbols and constants.

Constants

All constants shown in **Table 1** are calculated from only 4 cycles of charge-discharge measurement results shown in **Fig.3** by the least-squares method. The test battery is 70 Ah VRLA battery (SLC70 made by GS Yuasa Corporation).

First, the constants about electromotive force **E** are calculated from the measurement results of the part of step change.

The constants about voltage drop **V_d** are calculated from the measurement results of the same part and the relation between **E** and **SOC** and **T_{25}** calculated above.

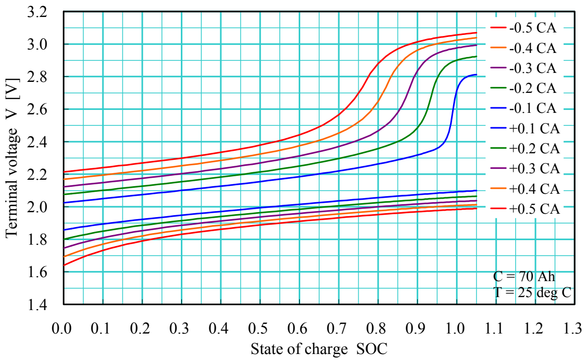

Fig.4: Simulation result from the model (V - SOC)

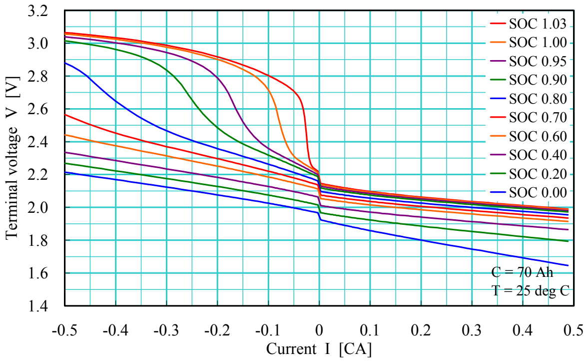

Fig.5: Simulation result from the model (V - I)

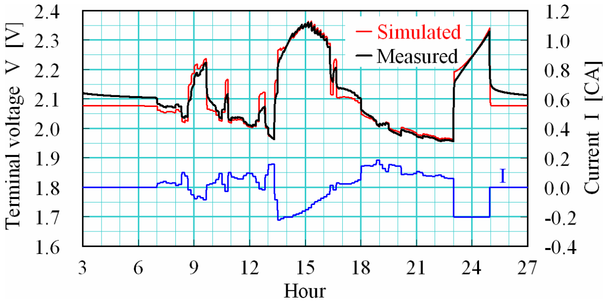

Fig.6: Verification test result (17 deg C)

The constants about voltage rise **V_g** are calculated from the measurement results during charge and **E** and **V_d** estimated from **I**, **SOC**, and **T_{25}**.

It is also possible to simulate without measurements if the constants are scaled by the scaling factor **K**.

$$K = \frac{C}{70\,[\mathrm{Ah}]} \tag{24}$$

C is the capacity of battery to simulate. **Table 1** shows scaling factors of constants.

SIMULATION RESULT

Simulation results from the model are shown in **Fig.4** and **Fig.5**. These results show natural curves. Terminal voltages in various conditions are calculated by a simple calculation of substitution.

VERIFICATION TEST RESULT

Fig.6 shows a verification test result at 17 deg C of battery temperature. At this point, the test pattern of battery current was decided by the PV system simulation based on the irradiance data and the residential electric power consumption data measured in Tokyo.

There are the voltage estimation errors. But the errors are in the small current area, so there are little estimation errors of power. Power estimation error ratio was 0.5 % at 17 deg C and 32 deg C of battery temperature. High precision was confirmed.

CONCLUSIONS

To simulate systems including batteries such as the grid-connected photovoltaic systems that less depends on the utility grid, the authors propose a new simulation model of battery characteristics. It can simulate a battery with high precision without complex handling.

The authors are defining detailed procedure for modeling in order to be more useful.

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Table 1: Symbols and constants of battery simulation model

Symbol	Discharge	Charge	Unit	Scaling	Remarks
V					Terminal voltage
E					Electromotive force of appearance
E_0					E at SOC = 1 (full charge)
E_1					SOC coefficient of E
S_E					SOC curvature of E
E_{00}	2133	2219	mV	1	E_0 at T = 25 deg C
α_{E0}	0.00016	-0.00032	1/℃	1	Temperature coefficient of E_0
E_{10}	589	705	mV	1	E_1 at T = 25 deg C
α_{E1}	0.0028	0.0038	1/℃	1	Temperature coefficient of E_1
S_{E0}	3.082		-	1	S_E at T = 25 deg C
α_{SE}	0.00687		1/℃	1	Temperature coefficient of S_E
V_d					Voltage drop by current
R					Resistance component of V_d
V_a					Maximum of saturation component of V_d
I_a	7.53	5.85	A	K	Current at 63% of saturation component of V_d
R_0					Constant component of R
R_1					SOC component coefficient of R
S_R	0.201	0.167	-	1	SOC shift at 2.7 times of SOC component of R
R_{00}	3.29	5.84	mΩ	1/K	R_0 at T = 25 deg C
α_{R0}	-0.008	-0.017	1/℃	1	Temperature coefficient of R_0
R_{10}	5.97	20.16	mΩ	1/K	R_1 at T = 25 deg C
α_{R1}	-0.039	-0.028	1/℃	1	Temperature coefficient of R_1
V_{a0}					Constant component of V_a
V_{a1}	23	-43	mV	1	SOC component coefficient of V_a
S_a	0.345	-	-	1	SOC shift at 37% of SOC component of V_a
V_{a00}	25	-22	mV	1	V_{a0} at T = 25 deg C
α_{Va0}	-0.029	-0.022	1/℃	1	Temperature coefficient of V_{a0}
V_g					Voltage rise at final phase of charging
V_{ga}	-	213	mV	1	Half of maximum of V_g
S_b					SOC at inflection point of V_g
S_g					SOC curvature of V_g
S_{b0}					Maximum of S_b
β_b					Current coefficient of S_b
S_{g0}					Minimum of S_g
β_g	-	0.00027	1/A	1/K	Current coefficient of S_g
S_{b00}	-	1.044	-	1	S_{b0} at T = 25 deg C
αS_{b0}	-	0.00067	1/℃	1	Temperature coefficient of S_{b0}
β_{b0}	-	0.01066	1/A	1/K	β_b at T = 25 deg C
$\alpha\beta_b$	-	-0.0177	1/℃	1	Temperature coefficient of β_b
S_{g00}	-	0.0146	-	1	S_{g0} at T = 25 deg C
αS_{g0}	-	-0.0272	1/℃	1	Temperature coefficient of S_{g0}