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Modeling of the Relation of SoC, SoH, DoD for VRLA Battery of Solar Power Plant in IT-PLN

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***Abstract*—Institut Teknologi PLN or IT-PLN in Jakarta has a solar power plant with capacity of 28.8 kW, which is operated only for research and teching. Due to limited access to the facility only two observation points of data have been collected. One in 2018 and one in 2020. The data are state-of-charge (SoC) and state-of-health (SoH) of the battery with type of DB BSB 12-100 produced by BSB Power Co. Ltd.. In 2018 the SoC is about 98.4% while the SoH is about 99%. In 2020 both parameters are 89% and 99%, respectively. Using a simple model consisted only of bulk capacitance C_{bulk}, surface capacitance C_{surf}, internal resistance R_{int}, and polarization resistance R_{pol}, we try to understand the obtained measurement values and use them to predict the working life of the battery. Since only two points of measurement, there could be a lot of solution will be obtained.**

Keywords*—state of charge, state of health, depth of charge, VRLA battery, solar power plan

I. INTRODUCTION

Operating philosophy of valve regulated lead acid (VRLA) battery and lithium iron phosphate (LFP) battery can be considered similar [1], which allows us to use common model for equivalent circuit model for a lithium-ion battery pack [2] based on Thevenin battery model [3], where both resistances increase during the use of the battery and the measuring impedance or admittance of VRLA batteries depends also on choice of the excitation signal and measurement frequency, where later will influence the available capacity calculation [4]. The common model will be used to simulate the state of charge (SoC), state of health (SoH), and depth of discharge (DoD) of the VRLA battery. A numerical approach using finite difference (FD) method is used to solve the differential equations relating current in resistors and capacitors combined in series – parallel arrangement. Such equivalent circuit model can also be used to simulate self-healing phenomenon during intermittent discharge of lithium batteries [5].

II. THEORY

A. Equivalent circuit

An equivalent circuit model for lithium-ion batteries with one RC branch [6] is used in this work as shown Figure 1, which is composed of two capacitors and two resistors.

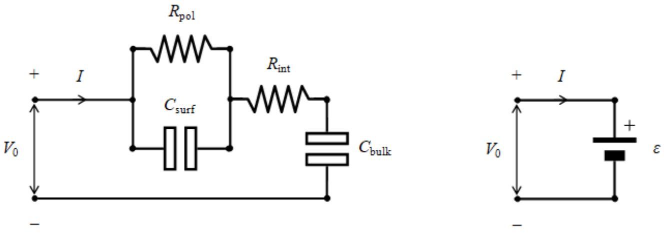

Fig. 1. Equivalent circuit of resistors and capacitors (left) is representing a lithium battery (right).

Four components are used in the equivalent circuit, where bulk capacitance C_{bulk}, surface capacitance C_{surf}, internal resistance R_{int}, and polarization resistance R_{pol} represent battery pack storage capacity, battery diffusion effect, electronic and ionic resistances, and reduction of the electric potential across the voltaic cell, respectively [2]. Battery pack terminal voltage and current are denoted by V_0 and I, which will have different direction in charging and discharging processes.

According to Kirchhof current law we can have that

$$I = I_{pol} + I_{surf} \quad (1)$$

and with the voltage law

$$V_0 = V_{surf} + IR_{int} + V_{bulk} \quad (2)$$

Ohm's law will give

$$V_{pol} = I_{pol}R_{pol} = V_{surf} \quad (3)$$

that relates I_{pol} adn R_{pol} to V_{pol}, which is also V_{surf}. Relation between charge q and current I will give

$$I_{\mathrm{surf}} = \frac{dq_{\mathrm{surf}}}{dt} = C_{\mathrm{surf}} \frac{dV_{\mathrm{surf}}}{dt} \tag{4}$$

and

$$I = \frac{dq_{\mathrm{bulk}}}{dt} = C_{\mathrm{bulk}} \frac{dV_{\mathrm{bulk}}}{dt} \tag{5}$$

Substitute Eqn. (3) to Eqn. (2) will give

$$V_0 = I_{\mathrm{pol}} R_{\mathrm{pol}} + I R_{\mathrm{int}} + V_{\mathrm{bulk}} \tag{6}$$

Use Eqn. (1) in Eqn. (6) will lead to

$$V_0 = I\left(R_{\mathrm{pol}} + R_{\mathrm{int}}\right) - I_{\mathrm{surf}} R_{\mathrm{pol}} + V_{\mathrm{bulk}} \tag{7}$$

We can further change Eqn. (7) using Eqns. (4) and (5) into

$$V_0 = \left(R_{\mathrm{pol}} + R_{\mathrm{int}}\right) C_{\mathrm{bulk}} \frac{dV_{\mathrm{bulk}}}{dt} - R_{\mathrm{pol}} C_{\mathrm{surf}} \frac{dV_{\mathrm{surf}}}{dt} + V_{\mathrm{bulk}} \tag{8}$$

Rearrange Eqn. (2) to get expression of V_{surf} and subsitute it to Eqn. (8) will produce

$$\begin{aligned} \left(1 + R_{\mathrm{pol}} C_{\mathrm{surf}} \frac{d}{dt}\right) V_0 &= \left(R_{\mathrm{pol}} + R_{\mathrm{int}}\right) C_{\mathrm{bulk}} \frac{dV_{\mathrm{bulk}}}{dt} \\ &+ R_{\mathrm{pol}} R_{\mathrm{int}} C_{\mathrm{surf}} \frac{dI}{dt} + R_{\mathrm{pol}} C_{\mathrm{surf}} \frac{dV_{\mathrm{bulk}}}{dt} + V_{\mathrm{bulk}} \end{aligned} \tag{9}$$

Substitute Eqn. (5) to Eqn. (9) to get

$$\begin{aligned} \left(1 + R_{\mathrm{pol}} C_{\mathrm{surf}} \frac{d}{dt}\right) V_0 &= V_{\mathrm{bulk}} \\ &+ \left[\left(R_{\mathrm{pol}} + R_{\mathrm{int}}\right) C_{\mathrm{bulk}} + R_{\mathrm{pol}} C_{\mathrm{surf}}\right] \frac{dV_{\mathrm{bulk}}}{dt} \\ &+ R_{\mathrm{pol}} R_{\mathrm{int}} C_{\mathrm{surf}} C_{\mathrm{bulk}} \frac{d^2}{dt} V_{\mathrm{bulk}}, \end{aligned} \tag{10}$$

which gives a second-order differential equation of V_{bulk}. We can define three time constant

$$\tau_1 = R_{\mathrm{pol}} C_{\mathrm{surf}} \tag{11}$$

$$\tau_2 = R_{\mathrm{int}} C_{\mathrm{bulk}} \tag{12}$$

$$\tau_3 = R_{\mathrm{pol}} C_{\mathrm{bulk}} \tag{13}$$

that will simplify Eqn. (10) into

$$\begin{aligned} \left(1 + \tau_1 \frac{d}{dt}\right) V_0 &= V_{\mathrm{bulk}} + \left(\tau_3 + \tau_2 + \tau_1\right) \frac{dV_{\mathrm{bulk}}}{dt} \\ &+ \tau_1 \tau_2 \frac{d^2}{dt} V_{\mathrm{bulk}} \end{aligned} \tag{14}$$

If we can get the solution of V_{bulk}, then using Eqn. (4) we can have I and then using Eqn. (2) V_{surf} will be obtained.

B. *Finite Difference*

Eqn. (14) will be solved numerically using finite difference (FD) in the form of

$$\frac{dV}{dt} \approx \frac{V(t + \Delta t) - V(t)}{\Delta t} \tag{15}$$

for first derivative and

$$\frac{d^2 V}{dt} \approx \frac{V(t + \Delta t) - 2V(t) + V(t - \Delta t)}{\Delta t^2} \tag{16}$$

for second derivative.

C. *Numerical Equation*

Eqns. (15) and (16) are implemented in Eqn. (14) to get the numerical equation. In the left side of Eqn. (14) the terms are

$$V_0 \equiv V_0(t) \tag{17}$$

and

$$\tau_1 \frac{dV_0}{dt} \equiv \frac{\tau_1}{\Delta t} V_0(t + \Delta t) - \frac{\tau_1}{\Delta t} V_0(t) \tag{18}$$

while in the right side they are

$$V_{\mathrm{bulk}} \equiv V_{\mathrm{bulk}}(t) \tag{19}$$

$$\begin{aligned} \left(\tau_3 + \tau_2 + \tau_1\right) \frac{dV_{\mathrm{bulk}}}{dt} &\equiv \frac{\tau_3 + \tau_2 + \tau_1}{\Delta t} V_{\mathrm{bulk}}(t + \Delta t) \\ &- \frac{\tau_3 + \tau_2 + \tau_1}{\Delta t} V_{\mathrm{bulk}}(t) \end{aligned} \tag{20}$$

and

$$\begin{aligned} \tau_1 \tau_2 \frac{d^2}{dt} V_{\mathrm{bulk}} &\equiv \frac{\tau_1 \tau_2}{\Delta t^2} V(t + \Delta t) - 2 \frac{\tau_1 \tau_2}{\Delta t^2} V(t) \\ &+ \frac{\tau_1 \tau_2}{\Delta t^2} V(t - \Delta t) \end{aligned} \tag{21}$$

From Eqn. (19) – (21) we can have

$$\begin{aligned} &\left(1 - \frac{\tau_1 + \tau_2 + \tau_3}{\Delta t} - 2 \frac{\tau_1 \tau_2}{\Delta t^2} V\right) V_{\mathrm{bulk}}(t) \\ &+ \left(\frac{\tau_1 + \tau_2 + \tau_3}{\Delta t} + \frac{\tau_1 \tau_2}{\Delta t^2}\right) V_{\mathrm{bulk}}(t + \Delta t) \\ &+ \frac{\tau_1 \tau_2}{\Delta t^2} V_{\mathrm{bulk}}(t - \Delta t) \end{aligned} \tag{22}$$

which is the right side of Eqn. (14) and from Eqns. (17) and (18)

$$\frac{\tau_1}{\Delta t} V_0(t + \Delta t) + \left(1 - \frac{\tau_1}{\Delta t}\right) V_0(t) \tag{23}$$

which is the left side of Eqn. (14). Equate Eqns. (22) and (23) will give

$$V_{\mathrm{bulk}}(t + \Delta t) = \frac{\frac{\tau_1}{\Delta t} V_0(t + \Delta t) + \left(1 - \frac{\tau_1}{\Delta t}\right) V_0(t) - \left(1 - \frac{\tau_1 + \tau_2 + \tau_3}{\Delta t} - 2 \frac{\tau_1 \tau_2}{\Delta t^2} V\right) V_{\mathrm{bulk}}(t) - \frac{\tau_1 \tau_2}{\Delta t^2} V_{\mathrm{bulk}}(t - \Delta t)}{\left(\frac{\tau_1 + \tau_2 + \tau_3}{\Delta t} + \frac{\tau_1 \tau_2}{\Delta t^2}\right)} \tag{24}$$

We can simplify Eqn. (24) by defining

$$c_1 = \frac{\tau_1}{\Delta t} \quad (25)$$

$$c_{12} = \frac{\tau_1 \tau_2}{\Delta t^2} \quad (26)$$

and

$$c_{123} = \frac{\tau_1 + \tau_2 + \tau_3}{\Delta t} \quad (27)$$

Eqns. (25) – (27) will turn Eqn. (24) into

$$V_{\mathrm{bulk}}(t + \Delta t) = \frac{c_1 V_0(t + \Delta t) + (1 - c_1)V_0(t) - (1 - c_{123} - 2c_{12}V)V_{\mathrm{bulk}}(t) - c_{12}V_{\mathrm{bulk}}(t - \Delta t)}{(c_{123} + c_{12})} \quad (28)$$

Eqn. (28) will give the solution of $V_{\mathrm{bulk}}(t)$, which can give another variable, I and V_0 for the battery. Using Eqn. (5) we can have

$$I(t) = C_{\mathrm{bulk}} \frac{\Delta V_{\mathrm{bulk}}}{\Delta t} = C_{\mathrm{bulk}} \frac{V_{\mathrm{bulk}}(t + \Delta t) - V_{\mathrm{bulk}}(t)}{\Delta t} \quad (29)$$

and from Eqn. (2) it can be obtained that

$$V_{\mathrm{surf}}(t) = V_0(t) - I(t)R_{\mathrm{int}} + V_{\mathrm{bulk}}(t) \quad (30)$$

if $V_0(t)$ is known from the measurement.

D. *Calculation of SoC, DoD, and SoH*

State of Charge (SoC) of a battery can be calculated using Coulomb counting method through

$$\mathrm{SOC} = \mathrm{SOC}(t) + \frac{1}{C_{\mathrm{rated}}} \int_{t_0}^{t_0+\tau} (I - I_{\mathrm{loss}})dt \quad (31)$$

with SOC(t_0), C_{rated}, I, and I_{loss} stand for initial SOC, rated capacity, battery current, and current consumed by the loss reaction [2]. For a battery there are terms of releasable capacity $C_{\mathrm{releasable}}$, battery rated capacity C_{rated}, and maximal releasable capacity C_{max}. SOC is defined as ratio of the releasable capacity $C_{\mathrm{releasable}}$ to the battery rated capacity C_{rated} as

$$\mathrm{SOC} = \frac{C_{\mathrm{releasable}}}{C_{\mathrm{rated}}} \times 100\% \quad (32)$$

which is more practical in use than Eqn. (31). There is maximal releasable capacity C_{max} of a fully charged battery, which can be different from the C_{rated}, where C_{max} will decline with the used time. The Cmax can be used to evaluate battery state of health (SOH)

$$\mathrm{SOH} = \frac{C_{\mathrm{max}}}{C_{\mathrm{rated}}} \times 100\% \quad (33)$$

In discharging mode there is depth of discharge (DOD)

$$\mathrm{DOD} = \frac{C_{\mathrm{released}}}{C_{\mathrm{rated}}} \times 100\% \quad (34)$$

where C_{released} is the capacity discharged by any amount of current. Eqn. (34) can also have another form

$$\mathrm{DOD}(t) = \mathrm{DOD}(t_0) + \Delta\mathrm{DOD} \quad (35)$$

where

$$\Delta\mathrm{DOD} = -\frac{1}{C_{\mathrm{rated}}} \int_{t_0}^{t_0+\tau} I_b(t)dt \quad (36)$$

with τ is operating period. We can improve the accuracy of estimation by considering operating efficiency η and it will modify Eqn. (36) into

$$\mathrm{DOD}(t) = \mathrm{DOD}(t_0) + \eta\Delta\mathrm{DOD} \quad (37)$$

where there are η_c during charging and η_d during discharging as defined in Murnane and Ghazel [2].

Without considering η and aging of the battery following equations hold

$$SOC(t) = 100\% - \mathrm{DOD}(t) \quad (38)$$

and

$$SOC(t) = \mathrm{SOH}(t) - \mathrm{DOD}(t) \quad (39)$$

III. EXPERIMENT

Using a software of Battery Management System, a measurements was carried out in 2020 and another one is provided by other observation [7] as shown in Table 1.

TABLE I. SOH AND SOC MEASUREMENT OF BSB DB 12-100 BATTERY (BSB POWER CO. LTD.).

Year	**SoC (%)**	**SoH (%)**	**Offgrid / Unloaded condition**
2018	98.4	99	good
2020	89	99	good

Through the Battery Management System software the measurement was performed automatically using standard setting, which are the same for both observations. From data sheet of BSB DB 12-100 $R_{\mathrm{int}} = 0.0045\ \Omega$ (full charged at 20 °C), and for 10 hours operation (10 A, 1.8 V) $C_{\mathrm{rated}} = 100$ Ah (at 25 °C).

IV. RESULTS AND DISCUSSION

A. *Analysis of* Observation Data

Using Eqns. (32) and (33) we can get $C_{\mathrm{rx}}^{Y_{\mathrm{obs}}}C_{\mathrm{x}}(Y_{\mathrm{obs}})$, where x = releasable, max and Y_{obs} is year of observation of the battery, which are

$$C_{\mathrm{releasable}}^{2018} = 98.4\mathrm{Ah} \quad (40)$$

$$C_{\mathrm{releasable}}^{2020} = 89\mathrm{Ah} \quad (41)$$

$$C_{\mathrm{releasable}}^{2018} = 99\mathrm{Ah} \quad (42)$$

$$C_{\mathrm{releasable}}^{2020}(2020) = 99\mathrm{Ah} \quad (43)$$

Using data from Table 1 and Eqn. (38) we can have

$$\text{DOD}(2018) = 100\% - 98.4\% = 1.6\% \quad (44)$$

$$\text{DOD}(2020) = 100\% - 89\% = 11\% \quad (45)$$

and from Eqn. (39)

$$\text{DOD}(2018) = 99\% - 98.4\% = 0.6\% \quad (46)$$

$$\text{DOD}(2020) = 90\% - 89\% = 1\% \quad (47)$$

There are different in obtaining DOD in both years.

B. *Analysis of Model*

For equivalent in Figure 1 and data sheet of BSB DB 12-100 battery (R_{int} = 0.0045 Ω, τ = 10 h, I = 10 A, V_0 = 1.8 V, C_{rated} = 100 Ah).

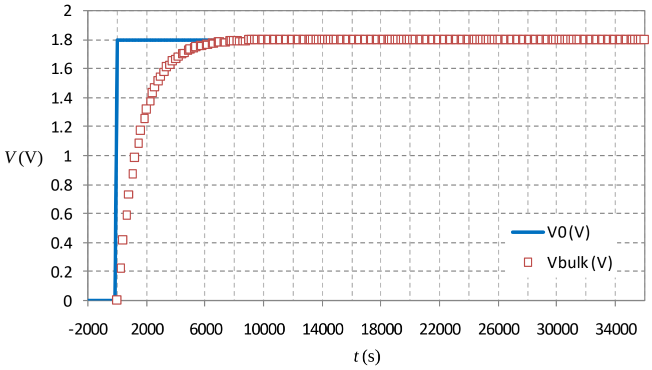

Fig. 2. Ideal bettery without R_{pol} and C_{surf} for the eqivalent circuit.

By setting Δt = 200 s and ignoring R_{pol} and C_{surf} we can have Figure 2, which is an example of an ideal battery representing by an ideal capacitor with small internal resistance.

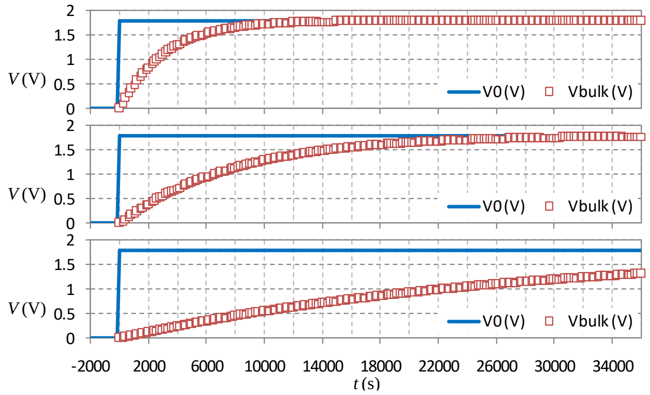

Fig. 3. Influence of R_{pol} / R_{int}: 1 (top), 4 (middle), 16 (bottom) with C_{surf} = 0.

R_{pol} will prevent the battery to achieve full charged state in the charging period as shown in Figure 3, where value of R_{pol} is presented as 1×R_{int}, 4×R_{int}, and 16×R_{int}. Final voltage of the battery remains the same as V_0.

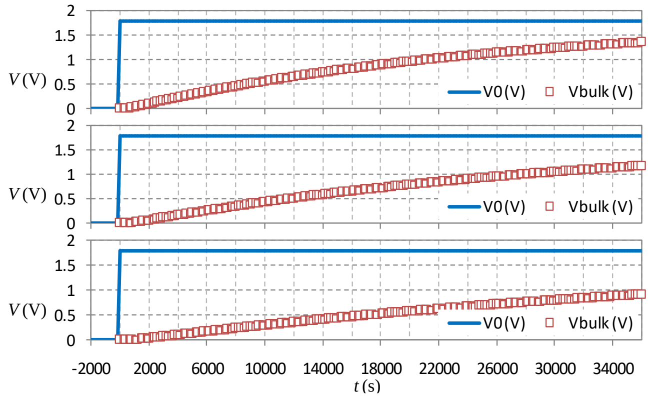

Fig. 4. Influence of C_{surf} / C_{bulf}: 0.5 (top), 1 (middle), 2 (bottom) with $R_{\text{pol}}/R_{\text{int}}$ = 10.

C_{surf} will prevent the battery or C_{bulk} to achieve the voltage V_0 as shown in Figure 4. Higher value of C_{surf} will give lower final voltage of C_{bulk}.

C. *Future Plan*

For lithium batteries the state-of-charge (SOC) can be monitored using impedance spectroscopy [8] and estimated using dual extended Kalman filter [9]. We could also use those also for VRLA in the future work.

V. CONCLUSION

An equivalent circuit for VRLA battery of a solar power plant in IT-PLN has been proposed. From observation data SOC and SOH form 2018 and 2020 do not give the same results in estimating DOD. Further analysis is required to have better understanding of performance of the battery.

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REFERENCES

[1] V. Karthigeyan, M. Aswin, L. Priyanka, K.N. Dileep Sailesh and K. Palanisamy, “A comparative study of lithium ion (LFP) to lead acid (VRLA) battery for use in telecom power system,” International Conference on Computation of Power, Energy Information and Commuincation (ICCPEIC), pp. 742-748, 2017.

[2] M. Murnane and A. Ghazel 2017 A Closer Look at State of Charge (SOC) and State of Health (SOH) Estimation Techniques for Batteries Analog devices 2 426-436

[3] S. Pai and M.R. Sindhu, “Intelligent driving range predictor for green transport,” IOP Conference Series: Materials Science and Engineering vol. 561, no. 1, pp. 012110, 2019.

[4] J. Badeda, M. Kwiecien, D. Schulte, and D.U. Sauer, “Battery state estimation for lead-acid batteries under float charge conditions by impedance: Benchmark of common detection methods,” Applied Sciences, vol. 8, no. 8, pp. 1308, 2018

[5] Z. Pei, X. Zhao, H. Yuan, Z. Peng, and Wu L 2018 An equivalent circuit model for lithium battery of electric vehicle considering self-healing characteristic Journal of Control Science and Engineering 5179758

[6] You HW, Bae JI, Cho SJ, Lee JM, and S-H. Kim, “Analysis of equivalent circuit models in lithium-ion batteries,” AIP Advances vol. 8, 2018.

[7] H. Rusdji, Efisiensi batre PLTS IT-PLN, Master Thesis, IT-PLN, Indonesia, 2018.

[8] P. Kurzweil and W. Scheuerpflug, “State-of-charge monitoring and battery diagnosis of NiCd cells using impedance spectroscopy,” Batteries, vol. 6, no. 4, 2020.

[9] X. Xu, D. Wu, L. Yang, H. Zhang, and G. Liu, Math. Probl. Eng. 2020.