Design of Control for Battery Storage Unit Converter

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Abstract. Battery storage will play an important part of systems supplied by photovoltaic or other renewable energy grid-connected sources. It is life-important to use appropriate battery management technique to achieve desired efficiency, long-life of battery unit and favorable costs. To ensure these demands, a precise control of batteries should consist of accurate State-of-Charge (SOC) estimation, effective balancing and charging control. The correct value of SOC is estimated using combination of Coulomb Counting and Kalman Filter methods. Performance of control for DC-DC converter with Double tiered capacity balancing circuit is analyzed. Battery management is verified using MATLAB/Simulink.

Keywords
Battery management, charge, discharge, balancer, state of charge, VRLA battery.

1. Introduction

Battery storage is a crucial part of many applications. For example, the increasing importance of energy accumulation in grid-connected photovoltaic power plants implies the meaning of precise battery management.

Battery management should handle not only charging and discharging batteries but also the safety of battery string, utilization the most of possible storage capacity of batteries, the prediction of age of batteries to estimate overall effectiveness of the system [1].

The management should consist of charge control, SOC and State-of-Health (SOH) estimation, balancing control, temperature and safety control. In this paper, control of static battery storage connected to the grid will be demonstrated. As battery storage are used 4 VRLA batteries. To estimate the SOC, Current Counting and Kalman Filter approaches are combined [2].

An important part of battery storage unit is balancer circuit. Performance of battery is getting worse by aging, significant influence have the temperature, not fully charged battery or long time inactivity with low SOC. Balancer enables effective usage of battery unit capacity. It has several functions such are cell voltage leveling, safety or extension of battery life [3]. Final control algorithm for DC-DC converter is verified by MATLAB/Simulink.

2. VRLA Battery Storage Unit

Battery system consists of bidirectional DC/DC converter which provides the charging and discharging of VRLA. Simplified battery management diagram is shown in Fig. 1. Battery management of the storage unit consists of SOC estimator, which is the most important part. Estimated SOC is used required by charge and balancer control.

![Battery management diagram](image)

2.1 DC-DC Converter and parameters of VRLA

Buck-boost topology was chosen for the DC-DC converter. Input capacitance $C_{in}$ was set to 0.68 mF, output capacitance $C_{out}$ to 42μF and inductance $L_{bb}$ to 3mH. Batteries are charged using constant voltage with current limit set to 1.5A as is defined in datasheet [4].

In Tab.1 are shown parameters of used VRLA battery. The battery storage unit has nominal voltage 48 V.

<table>
<thead>
<tr>
<th>VRLA battery parameters</th>
<th>Nominal Voltage 12V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Capacity</td>
<td>20h rate 7,2Ah</td>
</tr>
<tr>
<td>10h rate 6,5Ah</td>
<td></td>
</tr>
<tr>
<td>5h rate 5,9Ah</td>
<td></td>
</tr>
<tr>
<td>1h rate 4,3Ah</td>
<td></td>
</tr>
<tr>
<td>Internal resistance 22mΩ</td>
<td></td>
</tr>
<tr>
<td>Recommended charging Floating use 13,5-13,8V</td>
<td></td>
</tr>
<tr>
<td>Cycle use 14,4-15V</td>
<td></td>
</tr>
<tr>
<td>Maximum charging 1,5A</td>
<td></td>
</tr>
</tbody>
</table>

Tab. 1 VRLA parameters
2.2 Battery System Balancer Description

There are many balancer topologies and can be divided into two main types. Passive balancers use the dissipation to excess the stored charge and equalize the voltage among each battery cell or battery. Instead of energy dissipation, active balancers transfer the energy from the most charged cells to others using storing elements such as capacitors, inductors or transformers. In Fig. 2 are shown compared topologies and in Tab. 2 are compared parameters. Compared balancers are passive resistive (PR), switched capacitors (SCs), single switched capacitor (SC), double tiered capacitor (DTC), switched inductor (L), switched transformer (Tr) and converter balancer (Con) [5].

![Fig.2 Comparison of balancer topologies](image)

To balance the batteries, DTC balancer circuit is chosen and implemented in the system because of its favorable power losses, simplicity, average but satisfactory time of balancing. DTC has also smaller balancing time than SCs according [5]. Only drawback is the cost. The overall circuitry of battery charger is shown in Fig.3. Balancer control is simple, switches are switched oppositely.

![Fig.3 Charger with balancer](image)

2.3 SOC Description

There are many methods to estimate SOC. The most used is Current Coupling. It is based on the fact that capacity have specific amount of charge [6]. Counting the charge during discharge can lead to the value of SOC. It is defined by:

\[
SOC_{t+\Delta t} = SOC_t + \frac{1}{C} \int_{t}^{t+\Delta t} \eta \frac{dI}{dt}
\]

where \(SOC_t\) and \(SOC_{t+\Delta t}\) are values of SOC in time \(t\) and \(t+\Delta t\), \(C\) the capacity of VRLA, \(\eta\) efficiency of discharging or charging and \(I\) discharge/charge current.

This method has one major drawback. It is the error due the sample intensity and dependence of accurate sense of current. This means that SOC can be estimated for cycle performance without correction or modification because the error grows with operational time. Also, dynamical charge/discharge profiles increase the error [6]. To minimize this error, the SOC obtained by Current Coupling is updated by SOC estimated by Kalman Filter after 10s.

Kalman Filter is based on the battery model prediction and its correction to achieve the most possible solution. The electrical equivalents models are commonly used because of less complexity and necessity of special knowledge of battery chemistry although the electrochemical models are more accurate. Accuracy of SOC estimated by Kalman Filter depends significantly on the chosen battery model, process noise and measurement noise. Model is described using state equations:

\[
\begin{align*}
x_k &= A x_{k-1} + B u_k + w_k \\
y_k &= C x_k + v_k
\end{align*}
\]

where \(x_{k}\) is the state vector, \(u_k\) control vector, \(y_k\) measured vector, \(w_k\) the measurement noise, \(v_k\) the process noise, \(A\) the state matrix, \(B\) the control matrix and \(C\) the observation matrix.

<table>
<thead>
<tr>
<th>Topology</th>
<th>PR</th>
<th>SCs</th>
<th>SC</th>
<th>DTC</th>
<th>L</th>
<th>Tr</th>
<th>Con</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balance time</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Complexity</td>
<td>+++</td>
<td>+++</td>
<td>++</td>
<td>+++</td>
<td>++</td>
<td>++</td>
<td>+++</td>
</tr>
<tr>
<td>Efficiency</td>
<td>-</td>
<td>+++</td>
<td>++</td>
<td>+++</td>
<td>++</td>
<td>++</td>
<td>+++</td>
</tr>
<tr>
<td>Power</td>
<td>s</td>
<td>m-h</td>
<td>m-h</td>
<td>m-h</td>
<td>m</td>
<td>m-h</td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>+++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>+++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

Tab. 2 Comparison of balancer circuits parameters
Randle equivalent model of VRLA battery is chosen for Kalman filtering for its satisfying accuracy and relatively simplicity unlike other models. It is shown in Fig. 4. It consists of bulk capacitance describing the capacity of VRLA $C_b$, $R_{in}$ represents the inner series resistance of VRLA, $R_{t}$,$C_t$ circuit defines the dynamical transient behavior [7].

![Randle equivalent model of VRLA](image)

Equations which describe Randle battery model are:

$$
U_{bat} = U_{oc} + U_t + R_p I
$$

$$
\dot{U}_{oc} = \frac{R_{in} I - U_{oc}}{R_p C_b}
$$

$$
\dot{U}_t = \frac{R_I I - U_I}{R_t C_t}
$$

where $U_t$ is the voltage which represents transient behavior of battery, $U_{bat}$ voltage on terminals of VRLA, $I$ current, $R_p$ parallel resistance which represents the self-discharge.

Kalman Filter equations for linear system are:

$$
x_{kp} = A x_{k-1} + B u_k
$$

$$
P_{kp} = A P_{k-1} A^T + Q
$$

$$
S = C P_{kp} C^T + R
$$

$$
K = P_{kp} C^T S^{-1}
$$

$$
x_k = x_{kp} + K ( y_k - C x_{kp} )
$$

$$
P_k = (I - KC) P_{kp}
$$

where $x_{kp}$ is the prediction state vector, $P_{kp}$ covariance prediction, $x_k$ the new state vector, $P_k$ the new covariance, $R$ the measurement noise, $Q$ the process noise, $K$ the kalman gain, $I$ identity matrix and $S$ the innovation of covariance [8].

Matrixes for Randle model are defined:

$$
A = \begin{pmatrix}
-\frac{T_s}{C_b R_p} & 0 & 0 \\
0 & -\frac{T_s}{C_t R_t} & 0 \\
\frac{T_s}{C_t R_p} & \frac{T_s}{C_t R_t} & T_s
\end{pmatrix}
$$

$$
B = \begin{pmatrix}
\frac{T_s}{C_b} \\
\frac{T_s}{C_t} \\
\frac{T_s}{C_b} + \frac{T_s}{C_t}
\end{pmatrix}
$$

$$
C = (1 \ 0 \ 0)
$$

3. Simulation Results

SOC and Balancer simulation were done. SOC was estimated during several discharges with current 7A. Simulation step was set to 1s. Fig. 5 shows discharge profile of VRLA. In Fig. 6, estimated SOC from Current Coupling, Kalman Filter and their combination is shown. Detailed view on SOC estimation results is on Fig. 7. Accuracy of combined SOC method is suitable, the only drawback is the delay caused by Kalman Filter.
Balancer simulation was also analyzed by simulation. Capacities of balancer were set to 470 mF and protection resistances which limit the balance current were set to 30 mΩ. The switching frequency was set 1 kHz. Results of simulation are shown in Fig. 8, 9, 10. Batteries SOC were set to (37, 39, 43, 45 %) at the start of simulation. Balancer is activated during constant current charging (1,5 A) at time 10s and simulation time was set to 5000s. Initial and final values of SOC are compared in Tab. 3. Simulated performance is sufficient for energy storage with small charge/discharge dynamic.

4. Conclusion

Control of DC-DC converter for battery storage unit was analyzed in the paper. This control consisted of accurate SOC estimation, charging control and balancing of battery string.

Combination of Current Counting and Kalman Filter method of SOC was used. The value of SOC estimated by Current Counting was updated by the value obtained by Kalman Filter every 10 s. It has advantage of both approaches; it is relatively simple and still accurate.

As balancing circuit, the DTC was chosen. It has good parameters and can be used during charge and discharge.

In the future, temperature of battery will be added to the SOC estimation and also parameters of equivalent battery model will be estimated to enhance the accuracy of SOC prediction. This control will be part of static grid-connected system with energy storage.

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References

[4] FIAMM 20721/2 Datasheet

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**Martin GALÁD** was born in Lučenec, Slovakia in 1988. He earned his bachelor degree in Electrical Engineering in University of Žilina in Žilina, Slovakia in 2010. He got his Master degree in Electrical Drive in University of Žilina in 2012. Nowadays, he is a PhD. student at the Department of Mechatronics and Electronics, Faculty of Electrical Engineering, University of Žilina and his fields of study are stand-alone power systems, battery management.