Design of Bidirectional DC-DC Cuk Converter for Testing Characteristics of Lead-Acid Battery

Abstract. Lead-acid battery is an important element in the development of electric vehicle and hybrid generating power plant. In real circumstances, the capacity of the battery will change according to the amount of current discharged from the battery. In normal operation, it usually uses a voltage cut-off reference. The battery cut-off voltage limit, however, is usually obtained with a constant discharge current, which, in this case, cannot be done in a practical application. Another reference is by using state of charge (SoC) estimating method. The common method used for SoC estimation is coulomb counting because it can be done while batteries are connected to a grid. This research will test the discharge characteristic curve and estimate the SoC battery using coulomb counting. The battery tested is a type of valve regulated lead-acid (VRLA) with a rating of 7.2Ah and 12V. To implement the test system, DC-DC Bidirectional Cuk Converter is proposed with Average Current Mode Control, where the battery testing scheme is modified, so the power usage is more efficient. According to the testing results, the DC-DC converter is able to test VRLA battery with discharge and charge-discharge testing schemes. The charge-discharge cycle test on VRLA batteries shows that the results of using the coulomb counting method is more accurate than open circuit voltage method.

Keywords: Lead-Acid battery, state of charge, coulomb counting, Bidirectional DC-DC Cuk Converter.

Introduction

Nowadays, batteries are very important in some applications, such as electric vehicle, telecommunication system, renewable energy application, and power generations, either as a main system or secondary, for energy storage system. In order to obtain a good result, battery performance needs to be known by a user. For electric vehicles, the purpose of this study is to obtain the battery discharge characteristic curve and coulomb counting calculations for the SoC estimation by comparison using the open circuit voltage method.

In this research, a Valve Regulated Lead-Acid (VRLA) battery will be tested since it is commonly used for UPS and electric vehicles. The purpose of this study is to obtain the battery discharge characteristic curve and coulomb counting calculations for the SoC estimation by comparison using the open circuit voltage method.

On the other hand, coulomb counting method is most often used in industrial applications because it has good accuracy and can be done while battery is in operating condition. The coulomb counting method is to estimate SoC of the battery by calculating the current flowing in and out of the battery [5].

In this research, a Valve Regulated Lead-Acid (VRLA) battery will be tested since it is commonly used for UPS and electric vehicles. The purpose of this study is to obtain the battery discharge characteristic curve and coulomb counting calculations for the SoC estimation by comparison using the open circuit voltage method.

In this study, it also proposed a more efficient test of power where when the test battery is discharged; the wasted power will be used to charge the battery at the output side or another dummy battery. After the test is done dummy battery will be used in parallel with power supply to recharge the testing battery to increase the overall test efficiency. To implement the test system, it is necessary to use a DC-DC converter that is able to work both ways and has flexible conversion capabilities. Therefore, bidirectional DC-DC Cuk converter is used since it has bidirectional characteristic, able to convert in the same ratio as Buck-Boost Converter, so it could output higher or lower voltage from a constant input. Another advantage of this topology is that it has low current ripple from both of its input and output [6]. Proportional-Integral (PI) method is applied to the converter to get a constant current value on the test side and also when recharging the battery.

Valve Regulated Lead-Acid (VRLA) Battery

Lead-acid batteries are a type of battery that is often used in electric vehicles and hybrid generating systems because of the low cost of their production; robust to destructive use and high reliability. Valve regulated lead-
acid (VRLA) batteries are the development of lead acid batteries that utilize the oxygen recombination cycle, which is equipped with a one-way valve that works based on pressure so that changes in the amount of hydrogen do not affect the pressure on the battery. This makes VRLA batteries do not require frequent maintenance and has a longer charge-discharge cycle life than ordinary lead-acid batteries.

State of Charge (SoC)
State of Charge (SoC) refers to the ratio between left over battery capacity compared to the total capacity. In order to get long life battery usage, efficient and safely operated, the SoC of the battery needs to be monitored. However, since batteries are components that can store energy in form of chemical energy, hence monitoring the SoC value is slightly complex. So, to estimate the SoC of a battery is by measuring some parameters such as battery voltage; temperature; and internal resistance. Here are some methods for estimating the electric SoC of a battery shown as follows:

Coulomb Counting (CC)
Coulomb counting (CC) is one of the commonly used methods in determining battery SoC. The basic principle of the coulomb counting method is by estimating the SoC of a battery by calculating the incoming and outgoing currents from the battery. Here, the formula to be used for calculating the SOC of the battery.

\[
SoC = SoC_0 + \int_{t_0}^{t} \frac{I_d}{I_n} \, dt
\]

where SoC_0 is the initial SoC value right before the battery is used. CC method is commonly used, because it can be implemented when battery is in operating condition. The CC method, however, has a disadvantage because it does not consider the self-discharge and charging efficiency of the battery, so to avoid the accumulation of errors periodic recalibration is necessary.

Open Circuit Voltage (OCV)
Another method to estimate the SoC is Open Circuit Voltage (OCV) which estimates by using a reference value, which is the terminal voltage of a battery. The disadvantage of this method is that the battery terminal voltage when connected to a grid is constantly changing depending on its discharge current. If the battery is removed from a grid and given it a rest time, the voltage would become stable at a certain value. For lead-acid batteries, the voltage when the battery is discharged from the grid will be linearly proportional to the battery SoC. On the other hand, just after a lead-acid battery is released from a grid connection, the battery open circuit will be unstable until several minutes. Referring to other studies, the results of lead-acid battery SoC estimation with this method obtained an error result below 5% for break time or off-grid batteries for 10 minutes.

DC-DC Bidirectional Cuk Converter Design
A DC-DC Bidirectional Cuk Converter is a modified conventional DC-DC Cuk converter topology that can flow the current from in two ways, where the diodes in the conventional converter topology are replaced with MOSFET. This design has low current ripple at the input and the output, which provides an advantage that makes this design suitable for use in applications related to batteries.

The basic concept of bidirectional Cuk Converter is a combination of boost and buck topology that is consisted of the series capacitor with the function as an energy storage, where the output voltage can be adjusted higher or lower than the input voltage according to the duty cycle with reverse polarity on the output side. Similar to a conventional cuk converter at forward mode, MOSFET Q1 would work as a controlled switch by pulse width modulation (PWM) signal and Q2 would go off; hence it will work as a regular diode. Otherwise on backward mode the Q2 would be controlled by pulse width modulation (PWM) signal and Q1 would work as a regular diode. Here is the current flow during the steady state condition can be used to obtain the proper components of the converter.

DC-DC Cuk converter is actually formed by combination of boost and buck converter, where the energy from V_in is stored through C_1 before it is transferred in to V_out. Therefore, the voltage of C_1 can be simply defined as.

\[
V_{C_1} = \frac{1}{1-D} V_{in}
\]

D is a duty cycle of switching period to Q_1. On the other hand, the output voltage, a buck converter from input of V_{C_1}, can be determined as.

\[
V_{out} = D V_{C_1}
\]

Therefore, according to equation (1.2) and (1.3), the ratio between the output voltage towards the input voltage can be calculated as.
The parameters set through this experiment are shown in table 1, while the overall system implementation is shown in figure 5.

![Fig 5. The overall system implementation](image)

### Result and Analysis

This research presents the testing on lead acid battery, to obtain discharge characteristic curve and state of charge estimation using coulomb counting method. There are two types of testing, discharge characteristic curve scheme and charge-discharge cycle test scheme.

#### Discharge Characteristic Curve Scheme

Discharge characteristic curve testing is used to obtain a battery discharge curve. Before the test is done, firstly, each battery is set to the same OCV (Open Circuit Voltage) value so the battery SoC has the similar value. Coulomb counting method, then, is applied to reconfirm the SoC value of the batteries. In this test the battery has a voltage close to 13 V or SoC between 80-95% by using OCV. Afterwards, the battery is discharged using a different C-rate until the cut-off voltage value of each C-rate is reached. The battery voltage curve for each test is plotted and the battery capacity of each C-rate is estimated using the coulomb counting method. C-rates used in this test are C/5, C/10, and C/20.

After doing discharge characteristic curve test, it is obtained the results as shown in figure 6.

![Fig 6. Discharge characteristic curve results](image)

According to the curve above, it can be seen that with different C-ratings (C/5, C/10, and C/20), different curve characteristics will be obtained. According to the results, it can be seen that at C/5, with the highest discharge current of 1.25 A, it experiences the fastest voltage drop. On the other hand, the longest voltage drop is experienced with the lowest discharge current of 0.36 A, or C/20. The difference in voltage drop and battery capacity that occurs by giving
different discharge currents is caused by chemical reactions that convert chemical energy into electricity. This phenomenon occurs in batteries, resulting in power losses and a decrease in overall battery capacity which does not permanently happen.

Table 3. Discharge Characteristic Curve Results

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Voltage</td>
<td>13.1 V</td>
</tr>
<tr>
<td>Discharge Current</td>
<td>1.25 A</td>
</tr>
<tr>
<td>Cut-off Voltage</td>
<td>9.6 V</td>
</tr>
<tr>
<td>Testing Time</td>
<td>4 hours</td>
</tr>
<tr>
<td>Final Voltage</td>
<td>11.43 V</td>
</tr>
<tr>
<td>SoC initial CC</td>
<td>87%</td>
</tr>
<tr>
<td>SoC initial OCV</td>
<td>80-95%</td>
</tr>
</tbody>
</table>

This chemical reaction is electrically compared to the battery’s internal resistance. So by using the explanation of internal resistance, increasing the current passing through the battery will increase the power losses from the battery or, on other words, the efficiency of the battery will decrease. Furthermore, the greater the discharge current, it will also result a greater voltage drop.

Moreover, it can also be seen that the battery’s internal resistance causes that the cut-off voltage of each C-rating has a different value. The loading conditions which are constantly changing cause the use of cut-off voltage as a reference in the battery operation cannot be done. Therefore, other methods are highly needed to operate the battery efficiently or another reference also can be used is the state of charge (SoC) of the battery. It can be seen from the table of the SoC estimation methods that the coulomb counting method has good accuracy because it has a value similar to the results of the open circuit voltage (OCV) method which is a high-accuracy estimation method.

Charge-discharge cycle testing will be conducted to find out how coulomb counting works.

Charge-Discharge Cycle Test Scheme

After being charged using a constant current in accordance with the specified C-rate, the batteries are tested using charge-discharge cycle test to determine the initial battery SoC using the coulomb counting method. On this scheme, the battery is treated not to operated for 2 hours after the battery is fully-charged and reaches a cut-off voltage of 14.4 V (2.4 V x 6 cells). Therefore, the SoC can be estimated by OCV method. The battery is, then, re-discharged with the same C-rate as the charging and the coulomb counting method is, then, used to estimate the SoC when charging and discharge. Testing each C-rate will be done 3 times to get a value that is close to converging. This test uses C/6 and C/10 for C-rate values.

The following figure is an SoC graph of the charge-discharge testing cycle at C/6 and C/10.

In figure 7, it can be seen that the average value of the battery State of Charge (SoC) in the charge-discharge cycle for a C/6 rate is 70.41%, while, according to the estimation using open circuit voltage (OCV) method, the SoC is obtained between 60-80%. For the C/10 rate, the average battery SoC for three charge-discharge cycles is 75.72% where the results from the estimation using OCV are 70-85%. With a different C-rating, an estimation is obtained using coulomb counting which can determine the battery SoC accurately referenced from the Open Circuit Voltage method which is a method of estimating the SoC with a high degree of accuracy.

Fig. 7. Charge Discharge Cycle Test Results

According to the experimental results, it can also be known several disadvantages of the coulomb counting method that need to be considered. First is the level of accuracy of the current sensor used. It can be seen in C/6 test results in the first cycle that has a significant difference from the results in the second and third cycles. In addition, it can be seen from figure 7 that there is a trend that the estimated SoC when charging will be higher than that is discharging. This is caused since the coulomb counting method does not consider the charging and self-discharge efficiency of the battery. The coulomb counting method only calculates the current entering and leaving the battery. This is discussed in other studies [5].

However, according to the test results, it can be concluded that the State of Charge (SoC) estimation method using coulomb counting has high accuracy. In addition this method can be done when the battery is connected to the grid and in a working state, in contrast to the OCV method where the battery must be removed from the grid and requires a long rest time before testing. Some disadvantages of the coulomb counting method can actually be overcome; firstly by using a current sensor with good accuracy; secondly by considering the coefficient of battery charging efficiency in the calculation, and thirdly by periodically recalibrating to avoid the accumulation of errors when reading the SoC.

Conclusion

According to the implementation and study results, it can be concluded that DC-DC bidirectional Cuk converter is able to test the characteristics of VRLA battery. On the discharge characteristic scheme, the higher the current discharged, C/5 rate or 1.25 A, the fastest the voltage drop is experienced. Furthermore, on charge-discharge test scheme, it shows more accurate results using the coulomb counting method than OCV method. This can be verified by comparing the results with other method, open circuit voltage estimation method, where with C/6 rate, the SoC of battery is 70.41% by using coulomb counting method, while it is around 60-80% using OCV method. Moreover, with C/10 rate, by coulomb counting method, the SoC of battery is measured 75.72%, while by OCV method it is around 70-85%. Therefore, the coulomb counting method is suitable for use in a Battery Management System (BMS) because it has high reliability in determining the battery's SoC conditions.

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