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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.*

***Streszczenie.** Akumulator kwasowo-ołowiowy jest ważnym elementem w rozwoju pojazdów elektrycznych i elektrowni hybrydowych. W rzeczywistych warunkach pojemność akumulatora zmienia się w zależności od wartości prądu pobieranego z akumulatora. Graniczne napięcie odcięcia akumulatora jest zwykle wyznaczane przy stałym prądzie rozładowania, czego w nie można zrobić w praktycznym zastosowaniu. Innym sposobem oceny jest zastosowanie metody szacowania stanu naładowania (SoC). Powszechną metodą stosowaną do oszacowania SoC jest zliczanie kulombowskie, ponieważ można to zrobić, gdy akumulatory są podłączone do sieci. Badanie to sprawdzi krzywą charakterystyki rozładowania i oszacuje akumulator SoC za pomocą zliczania kulombowskiego. Aby wdrożyć system testowy, proponuje się dwukierunkowy konwerter DC-DC z kontrolą trybu średniego prądu, w którym zmodyfikowano schemat testowania baterii, dzięki czemu zużycie energii jest bardziej wydajne. Test cyklu ładowania-rozładowania akumulatorów VRLA pokazuje, że wyniki zastosowania metody zliczania kulombowskiego są dokładniejsze niż metoda napięcia w obwodzie otwartym. (**Wdrożenie dwukierunkowego przetwornika DC-DC Cuk z kontrolą trybu średniego prądu do testowania charakterystyki akumulatora ołowiowo-kwasowego**).*

Keywords: Lead-Acid battery, state of charge, coulomb counting, Bidirectional DC-DC Cuk Converter..
Słowa kluczowe: akumulator kwasowo-ołowiowy, stan naładowania, zliczanie kulombowskie, dwukierunkowy konwerter Cuk DC-DC.

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, such as its capacity (Ampere-hours/Ah) or watts per cell (w/c). In many cases, batteries are generally chosen by its Ampere-hours (Ah) capacity [1]. In real system, however, a battery cannot be determined only by observing its capacity, but also the derating factor that affects the overall battery capacity needs to be considered. Batteries are usually discharged at different discharge rate, which refers to the current flowing from the batteries. The higher the average current supplied by a battery, the more capacity will be reduced [2], [3]. However, each type of battery has different discharge rate and capacity, so it needs methods to know the remaining capacity of a battery, which is usually referred to State of Charge (SoC). Therefore, it can keep the use of batteries in normal operation. Generally, to keep the battery in normal operating voltage, cut off voltage reference can be used to estimate the capacity of a battery. But, the problem is when determining cut-off reference based on a datasheet, it can be obtained that the discharge variable form the battery has a constant current characteristic, which is hard obtained since the discharge current will vary according to the load.

There are several methods to estimate the State of Charge (SoC) of the battery using several battery parameters that can be measured such as open circuit voltage; coulomb counting and Kalman filter [4]. Open Circuit Voltage (OCV) method is the most accurate to determine the SoC of a battery. Still, OCV method is difficult to determine the SoC while the battery is being operated. 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 are 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 priciple 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.

(1) $$SoC = SoC_0 + \int_{t_0}^{t} I_d$$

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.

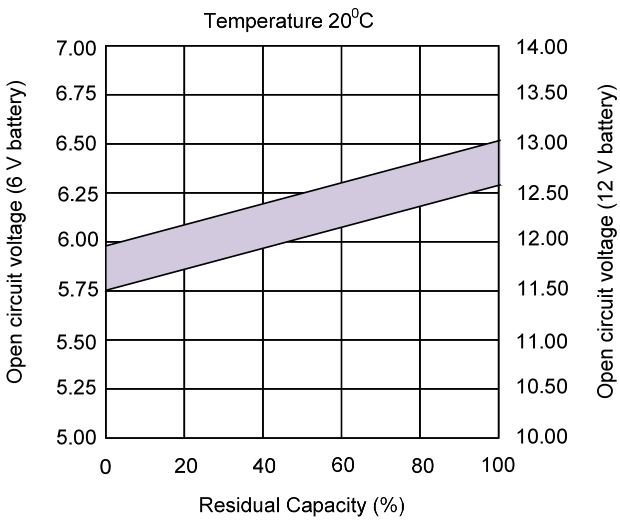

Fig 1. VRLA battery SoC comparison with OCV [7-8]

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.

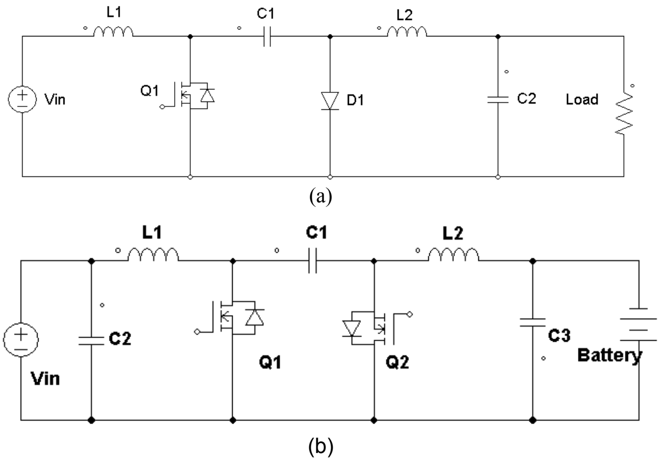

Fig. 2. DC-DC Cuk Converter (a) Conventional topology (b) Proposed Bidirectional DC-DC Cuk Converter topology

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 backward and forward mode of the converter, and 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.

(2) $$V_{C_1} = \frac{1}{1-D} V_{in}$$

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_{C1}, can be determined as.

(3) $$V_{out} = D V_{C_1}$$

Therefore, according to equation (1.2) and (1.3), the ratio between the output voltage towards the input voltage can be calculated as.

(4) $$V_{out} = \frac{D}{1-D} V_{in}$$

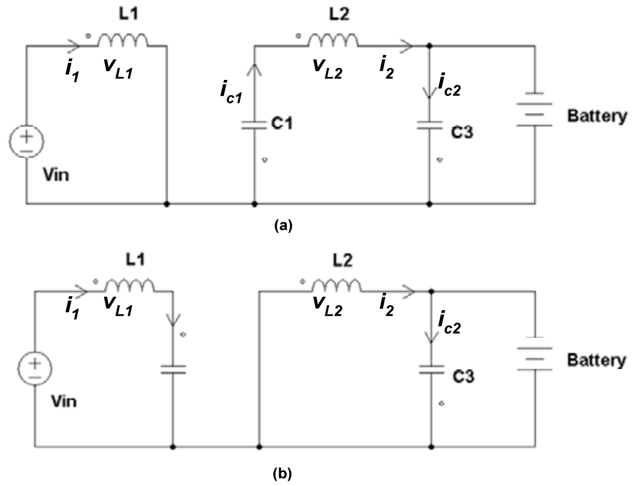

Fig 3. Cuk Converter current flows (a) switch-on backward mode (b) switch-off forward mode

Implementation and Experimental Setup

Bidirectional DC-DC Cuk converter is used for testing a VRLA battery. Average Current Mode Control is used as a control method for obtaining a constant average current of the inductor in the converter. By varying the value of the duty cycle, the discharge current for battery testing can be kept constant. Duty cycle is set automatically by comparing the value of the inductor current on the test side with the reference value to get an error value which will then be processed using the Proportional Integral (PI) control. Using the reference value of the PI control will set the duty cycle to get an error value close to zero, or in other words the inductor current on the test side approaches the specified value. The scheme of the control method is shown in figure 4.

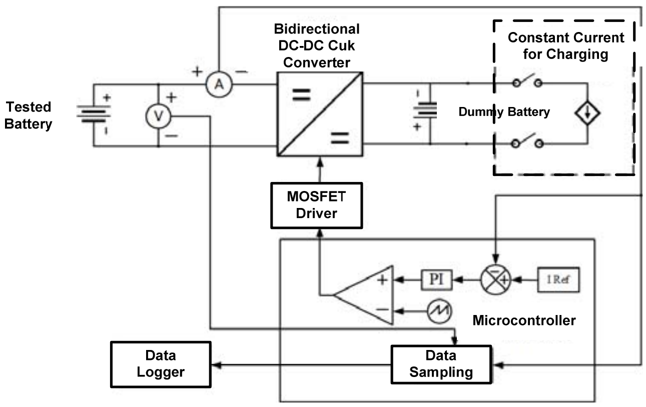

Fig 4. Battery testing scheme with Bidirectional DC-DC Cuk Converter using Average Current Mode Control

Table 1. Testing Parameters

Battery Parameters	**Value**
VRLA Battery	LC-V127R2
Voltage Nominal	12 V
Rating Capacity	7,2 Ah
Converter Parameters	**Value**
Switching Frequency	20 kHz
Output Power	60 watt
L1 and L2 inductor	1,6 mH
C1 Capacitor	330uF/250V
C2 and C3 Capacitor	1000uF/63V
MOSFET 1 and 2	IRFP 4332
Driver MOSFET (2)	TLP 250

The parameters set trough this experiment are shown in table 1, while the overall system implementation is shown in figure 5.

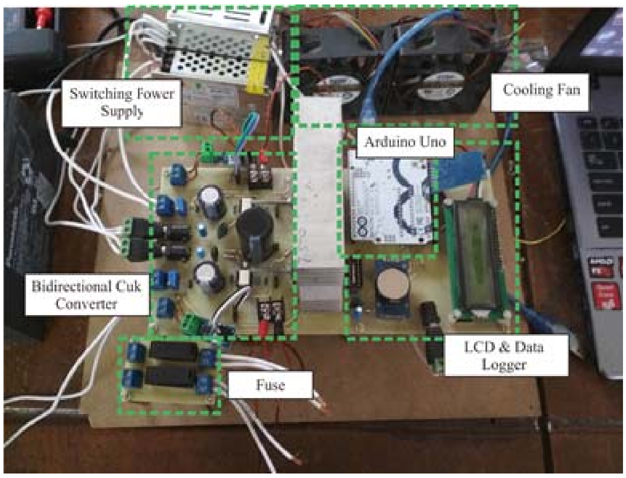

Fig 5. The overall system implementation

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.

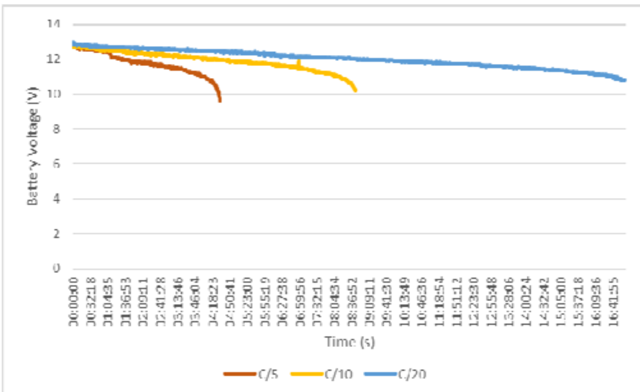

Fig. 6. Discharge characteristic curve results

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

Parameters	Value		
	C/5	C/10	C/20
Intital Voltage	13.1 V	13.08 V	13 V
Discharge Current	1.25 A	0.66 A	0.36 A
Cut-off Voltage	9.6 V	10.2 V	10.8 V
Testing Time	4 hours 21 minutes	8 hours 36 minutes	17 hours 4 minutes
Final Voltage	11.43 V	11.5 V	11.21 V
SoC initial CC	87%	86%	85.30%
SoC initial OCV	80-95%		

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.

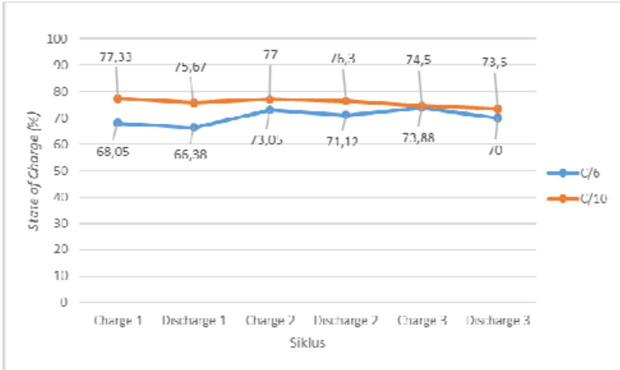

Fig. 7. Charge Discharge Cycle Test Results

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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