Multi-step constant current-constant voltage charging method to improve CC-CV method on lead acid batteries

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ABSTRACT

Constant current-constant voltage (CC-CV) is one of the battery charging methods that is commonly used. However, this method has several drawbacks, including the charging current in constant current (CC) mode, which can only be set to a maximum of 0.3 C on lead acid batteries, resulting in a relatively long charging duration. Therefore, in this research, the multi-step constant current-constant voltage (MCC-CV) method of battery charging system is developed where this method can use a greater charging current, resulting in a significant reduction in charging duration by using multiple current setpoints in MCC mode, with the initial setpoint current can be set beyond 0.3 C, which is 0.34 C in this system. This system uses a DC-DC single-ended primary inductance converter (SEPIC) converter as a battery charging control system, equipped with a power cut-off relay when the charging current reaches 0.05 C in constant voltage (CV) mode. From the test results obtained, the MCC-CV method can charge the battery to its full capacity faster than the CC-CV method with a difference of 15.34 minutes and the relay on the system can work properly.

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1. INTRODUCTION

Secondary batteries are becoming more popular in energy storage systems for modern technologies such as electric vehicles, renewable energy storage systems, smart grid systems, backup energy systems in ATS, and many other applications [1]-[6]. Lead acid batteries are one of the types of secondary batteries that are rechargeable [7], [8]. The advantage of this battery is that its maintenance costs are cheaper than other types of secondary batteries, making it suitable for use in industry and households [9], [10].

Practically, there are several methods of charging batteries, such as the constant current-constant voltage (CC-CV) method [3], [11]. The CC-CV charging method combines the constant current (CC) charging process, followed by the constant voltage (CV) method [12], [13]. In the CC-CV charging method applied to lead acid batteries, the CC mode setpoint current value can only be set between 0.1 C-0.3 C, resulting in a relatively long battery charging duration [14]. If regulated beyond 0.3 C, it can potentially damage the battery caused by a large current at a large battery charging voltage. Overcharging can also occur in the battery charging process when the battery capacity is already full and the CV charging process is still working, which can damage the battery [3]. To achieve CC charging above 0.3 C, a charging system that can change the current setpoint value when the cut-off voltage is reached is needed, thereby reducing the potential for reduced battery life and shortening the battery charging duration.

Based on the problem mentioned above, a multi-step constant current-constant voltage (MCC-CV) battery charging method is proposed in this journal. In this charging method, several charging current setpoints are determined and then continued with the constant voltage charging method to maximize battery charging to full battery capacity. In this study, the DC-DC single-ended primary inductance converter (SEPIC) converter is used as a battery charging system to regulate the output value of current and voltage to the battery according to the MCC-CV method that has been designed. SEPIC converters were chosen for their high power efficiency, reduced current ripple on the input and output sides of the converter, and non-inverting output voltage polarity [15], [16] To prevent potential overcharging, the system uses a relay to cut off the power flow to the battery when the battery charging current reaches 0.05 C in CV mode. The battery used in the system is a lead-acid battery. In the MCC-CV method, the current value can be set beyond 0.3 C in lead acid batteries, where in this system, a current of 0.34 C is used in the first current step, then the setpoint current value is set lower in the next step.

2. RESEARCH METHOD

From the block diagram of Figure 1, a battery charging system is made using a SEPIC converter, where the charging method used is the MCC-CV method. In the charging method, several charging steps are applied with different CC until the battery capacity is full, with the current value in the initial step high and the current value decreasing at each step switch. Switching the charging current step occurs when the charging voltage is close to the battery cut-off voltage value. When the mode switching condition at the last current step is met, the charging method changes from MCC to CV. The voltage source in the system uses a power supply to supply power that will be stored in the battery. The parameters used in the system can be seen in Table 1.

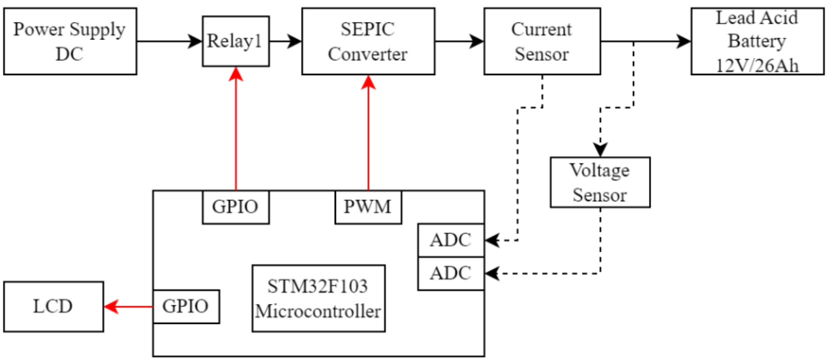

Figure 1. MCC-CV charging system block diagram

Table 1. System parameter

Component	Description
Battery type	Lead acid battery
Battery capacity	26 Ah
Battery terminal voltage	12 volt
Battery cut off voltage (V cut-off)	14.4 volt
DC-DC converter	SEPIC converter
Microcontroller	STM32F103C8T6
Current and voltage sensor	ACS712, voltage divider

2.1. Multi-step constant current–constant voltage

MCC-CV has a working method similar to the CC-CV charging method, but in the CC charging method, several current steps are determined to maximize the time used for charging. In the charging method, several steps are applied with different constant setpoint currents until the last current step, with the current value in the initial step high and the current value decreasing at each step displacement [17]. Current step switching is performed when the battery charging voltage reaches the battery cut-off voltage value. During the step switching, the voltage at the battery terminals decreases due to the reduced charging current value, and then the voltage value will increase until it reaches the cut-off voltage value again. When the mode switching condition at the last current step is met, the method changes from MCC to CV. In the MCC-CV method, the setpoint current value can be set to exceed the safe limit value for the CC-CV method, whereas, in lead acid batteries, this MCC-CV method can set the initial setpoint current value to exceed 0.3 C [14]. Setting the setpoint above 0.3 C can effectively increase the charging power value of the battery, with the charging duration performed relatively faster than the CC-CV method. The graph of current and voltage characteristics of the MCC-CV method can be seen in Figure 2, while the algorithm of the MCC-CV method can be seen in Figure 3.

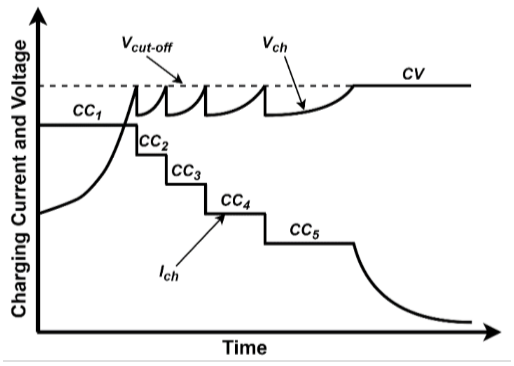

Figure 2. MCC-CV voltage and current waveforms

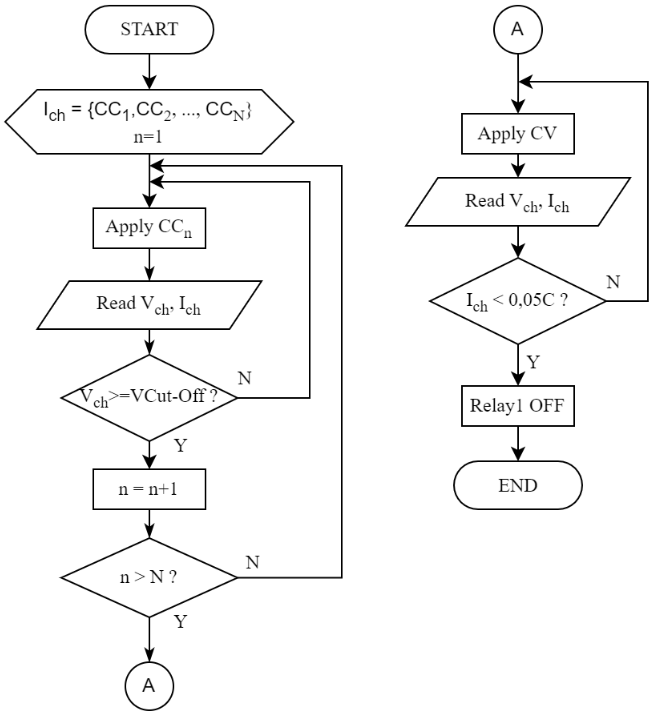

Figure 3. MCC-CV algorithm flowchart

Figure 3 explains how battery charging works. In the MCC-CV charging method in this system, the number of steps used is 5 in CC mode. The step change is carried out sequentially from CC1 to CC5 until the change from CC5 to CV mode. The charging current value at CC1 is determined from the battery rating used, the CC5 charging current value is determined randomly, and then the CC2, CC3, and CC4 current values can be calculated from the predetermined CC1 and CC5 values using (1) to (4) [18]:

$$\mathrm{CC2} = \sqrt{CC1\ x\ CC3} \quad (1)$$

$$\mathrm{CC3} = \sqrt{CC2\ x\ CC4} \quad (2)$$

$$\text{CC4} = \sqrt{CC3\ x\ CC5} \quad (3)$$

where the CC3 value can also be calculated using:

$$\text{CC3} = \sqrt{CC1\ x\ CC5} \quad (4)$$

notes: CC1 is setpoint current charging step 1; CC2 is setpoint current charging step 2; CC3 is setpoint current charging step 3; CC4 is setpoint current charging step 4; CC5 is setpoint current charging step 5; I_{ch} is battery charging current; V_{ch} is battery charging voltage; and $V_{Cut\text{-}Off}$ is voltage cut-off.

In this battery charging system, the first current step (CC1) is determined to be a setpoint of 0.34 C from the battery Ah, which is 9 A, the fifth current step (CC5) is determined to be a setpoint of 0.15 C from the battery Ah, which is 4 A. For the battery charging step displacement voltage value, a value of 14.4 V is determined. From the specified CC1 and CC5 values, then:

$$\text{CC3} = \sqrt{9\ x\ 4} = 6\ A$$

$$\text{CC2} = \sqrt{9\ x\ 6} = 7.35\ A$$

$$\text{CC4} = \sqrt{6\ x\ 4} = 4.9\ A$$

After obtaining the MCC-CV calculation, the value of the CC-CV planning is determined as a comparison method, where the CC-CV method uses a current of 0.3 C from the Ah battery, which is 7.5 A. From the results of the above calculations, the MCC-CV and CC-CV planning that will be compared can be seen in Table 2.

Table 2. Charging method design

Charging method	CC1	CC2	CC3	CC4	CC5	CV
MCC-CV	9 A	7.35 A	6 A	4.9 A	4 A	14.4 V
CC-CV	7.5 A					14.4 V

At the beginning of charging, the CC1 step current is used with a CC for the first battery charging condition. The CC1 current value will be used continuously until the charging voltage reaches the battery cut-off voltage value. When the charging voltage value reaches the battery cut-off voltage value, the charging current changes to the next step. A step change will always occur when the battery cut-off voltage is reached at each CC1-CC5 charging current step. At CC5, when the charging step switching voltage value is reached, the charging method will change from CC to CV, with the battery charging voltage value set constant at 14.4 V. The charging process in CV conditions will continue until the charging current decreases until it approaches 5% of the battery Ah, which is 1.3 A. When the current of 5% of the battery Ah is reached, the battery capacity has been indicated to be full, so Relay1 is then changed to an open condition to stop the battery charging process.

2.2. Single-ended primary inductance converter converter

Single-ended primary inductance converter or SEPIC converter is a type of converter that can produce the desired output voltage by increasing and decreasing the input voltage [19]-[22]. SEPIC Converter produces a voltage with the same polarity between the input and output voltage. The addition of capacitors and inductors to the SEPIC converter can also reduce current ripple [16], [20], [23], [24]. In this case, the value of the SEPIC input voltage parameter is 35.6 V, which is the output value of the power supply. The SEPIC output voltage parameter is 14.4 V, which is the battery charging voltage, so the duty cycle calculation can be obtained by calculating using (5) as [23]:

$$\text{V}_o = \frac{\text{V}_s \text{ x D}}{1-D} \quad (5)$$

notes: Vo is output voltage (V); Vs is input voltage (V); and D is duty cycle.

A SEPIC converter can adjust the output voltage to be greater or smaller than the input depending on the duty cycle that has been planned, so this converter is suitable for many applications [25]. The duty cycle value can be used to adjust the converter to increase and decrease the desired output. This converter generally also uses inductors, capacitors, diodes, and switching transistors for the calculation of inductors and capacitors can be seen in (6) and (8) as [19], [20]:

$$C = \frac{V_o \text{ x D}}{R\ x\ \Delta C1\ x\ f_S} \quad (6)$$

$$R = \frac{\text{Vo}}{\text{Io}} \quad (7)$$

$$L = \frac{\text{Vs x D}}{\Delta IL\ x\ f_S} \quad (8)$$

notes: R is resistance (Ω); L is inductor (H); C is capacitor (F); V_o is output voltage (V); V_s is input voltage (V); f_s is frekuensi (Hz); ΔIL is ripple current (A); and I_o is output current (A).

The planning of the SEPIC converter includes the amount of duty cycle influenced by the desired output voltage, which is in accordance with (5). In planning the SEPIC converter to reduce the voltage ripple, a filter is added from the capacitor at the input and output of the converter. Determination of the output current used in this system is obtained from 34% of the battery capacity used/0.34 C. As for determining the value of resistance, capacitance, and inductance obtained in (6)-(8). From the calculation using (6)-(8). the value of each component used to determine the output parameters of the sepic converter can be seen in Table 3.

Table 3. SEPIC converter design

Parameter	Value	Unit
V_s	35.6	Volt
V_o	14.4	Volt
I_s	5.62	A
I_o	9	A
f_s	40	kHz
L_1	228.042	µH
L_2	228.042	µH
C_1	4700	µF
C2	4700	µF

3. RESULTS AND DISCUSSION

Figure 4 shown experimental system setup. In the test results conducted, the MCC-CV method has been implemented on the charging system that has been made and then compared with the CC-CV method. In the first test with the graph image shown in Figure 5, the MCC-CV and CC-CV charging methods work when the initial battery voltage condition before charging testing is 12.08 V, which is then charged to full voltage in CV mode. In the second test with the graph image shown in Figure 6, the MCC-CV and CC-CV charging methods work when the initial battery voltage condition before the charging test is 12.17 V, which is then charged to full voltage in CV mode. Testing with different initial voltages is carried out to determine the effect of the MCC-CV method on different initial battery voltages and compare it to the CC-CV method. From the two tests carried out, data in the form of charging duration for each method with different initial battery voltages can be seen in Tables 4 and 5.

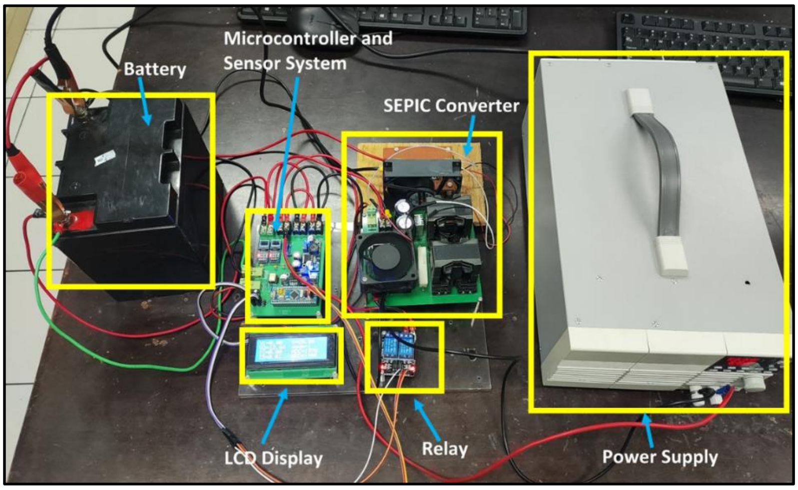

Figure 4. Experimental system setup

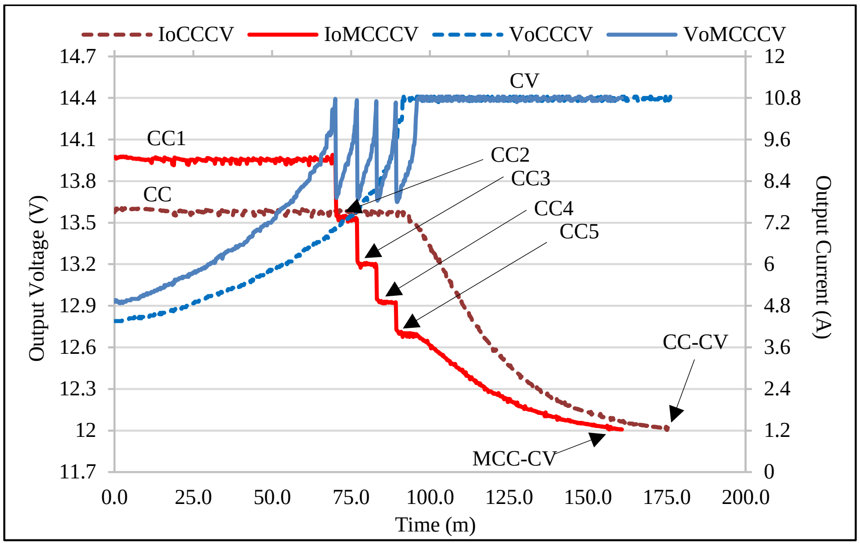

Figure 5. Battery charging 1st test result using MCC-CV and CC-CV method with initial battery voltage 12.08 V

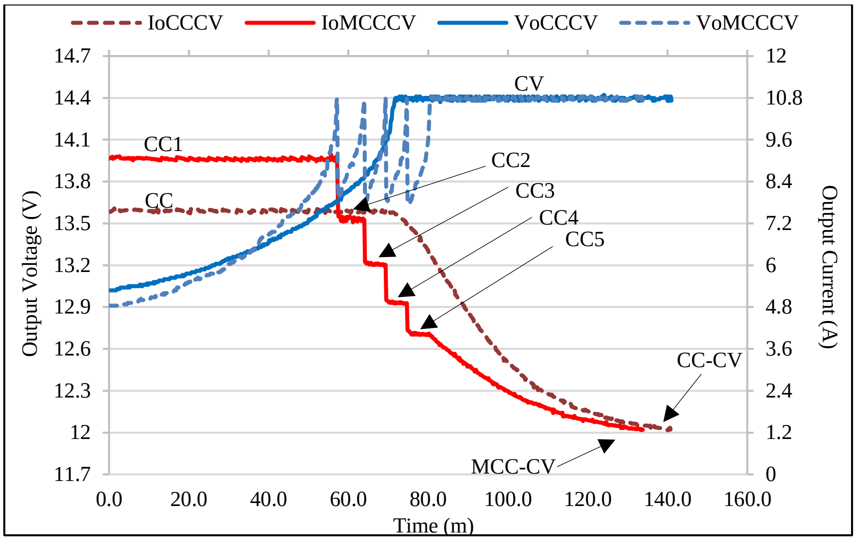

Figure 6. Battery charging 2nd test result using MCC-CV and CC-CV method with initial battery voltage 12.17 V

Table 4. Battery charging 1st test result using MCC-CV and CC-CV method with initial battery voltage 12.08 V

Charging method	Battery initial voltage	Charging time (m)						Total charging time (m)	Time difference (m)
		CC1	CC2	CC3	CC4	CC5	CV		
MCC-CV	12.08 V	70	6.83	6.17	6.17	6.67	65	160.83	15.34
CC-CV		91.17					85	176.17	

Table 5. Battery charging 2nd test result using MCC-CV and CC-CV method with initial battery voltage 12.17 V

Charging method	Battery initial voltage	Charging time (m)						Total charging time (m)	Time difference (m)
		CC1	CC2	CC3	CC4	CC5	CV		
MCC-CV	12.17 V	57.17	6.83	5.33	5.33	5.83	53.33	133.83	7.17
CC-CV		71.67					69.33	141	

Using the designed MCC-CV current step values, the CC2 to CC5 modes obtained relatively similar charging durations in both the first and second tests. The duration of CC1 and CV charging varies based on the initial battery voltage condition before charging, with the duration in both modes being faster in tests with higher initial battery voltage. The duration also applies to the CC-CV method. In test 1 of the MCC-CV method, a difference in charging duration of 15.34 minutes was obtained compared to the CC-CV method. This was also true in test 2, although the difference in charging duration between the MCC-CV and CC-CV methods was lower, at 7.17 minutes. The cause of the lower charging duration difference is due to the higher initial battery voltage condition before charging, causing a reduced charging duration in CC1 mode.

With the implementation of CV charging mode, the battery capacity can be met close to 100%, but the disadvantage of CV charging is the relatively long charging duration. The application of the MCC-CV method in the tests carried out succeeded in reducing the charging duration of the CV mode significantly, causing the total charging duration to be faster than the CC-CV mode. In the CC-CV method, the CV mode (14.4 V) works at a considerable current (0.3 C/7.5 A), potentially reducing battery life. By using the MCC-CV method, the CV mode (14.4 V) works after the mode switching condition at CC5 (0.15 C/4 A) is met, so the CV mode works with a lower uncontrolled current, which can reduce the potential for reduced battery life. The use of relays in the charging system can work as desired, as shown in Figures 4 and 5, where the charging power flow is cut off by the relay when the charging current in CV mode has reached 0.05 C/1.3 A.

4. CONCLUSION

After system testing, the MCC-CV method is proven to shorten the battery charging duration. Applying the MCC method can significantly reduce the charging duration in CV mode compared to the conventional CC-CV method. At an initial battery voltage of 12.08 V, the difference in charging duration is 15.34 minutes in testing the MCC-CV method with a CC1 current step of 0.34 C compared to the CC-CV method with a current of 0.3 C. In contrast, at an initial battery voltage of 12.17 V, the difference in charging duration is 7.17 minutes in testing the MCC-CV method with a CC1 current step of 0.34 C compared to the CC-CV method with a current of 0.3 C. The implementation of CV mode in the MCC-CV charging system can charge the battery capacity to nearly 100%. The charging power cut-off protection system using relays can work properly when the charging current in CV mode is close to 0.05 C current.

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