Design and Implementation of DC Fast Charging for 48V LiFePO4 Battery Pack

Windhu Griyasti Suci[1*], *Firman* Asto Putro[1], *Fandi* Surya Adinata[2], *Muhammad* Nizam[2], *Agus* Ramelan[2], and *Aida* Nur Ramadhani[3]

[1] Vocation school Universitas Sebelas Maret Surakarta, Indonesia
[2] Electrical Engineering Universitas Sebelas Maret Surakarta, Indonesia
[3] Chemical Engineering Universitas Sebelas Maret Surakarta, Indonesia

Abstract. This research focuses on developing a fast charging system to charge lithium-ion battery packs with a voltage rating of 48 volts. Standard battery charging uses a 0.25 C charging rate, which takes about 4 hours. The charging method in this study uses the constant current, constant voltage (CC-CV) method by adjusting the charging current at a charging rate of 1C, 2C, and 3C from the battery capacity. The buck converter determined the charging current value, setting it to produce a voltage of 53 V and a charging current of 10 A for a 1C charging rate, 20 A for a 2C charging rate, and 30 A for a 3C charging rate. Based on the testing, the battery charging time to reach 80% takes 57 minutes for charging rate 1C, 30 minutes for charging rate 2C, and 26 minutes for charging rate 3C.

1 Introduction

Lithium-ion batteries are becoming the battery of choice for many applications, such as grid systems [1] and electric vehicles [2],[3]. The lithium iron phosphate (LiFePO4) battery type is known to be environmentally friendly, affordable, and has good cycle and thermal stability [4],[5], making it suitable for use as an electric vehicle battery. There are two classifications for battery charging time: (1) slow charging and (2) fast charging. Slow charging uses low-power charging with a charging time of around 3–4 hours. On the other hand, fast charging systems provide more outstanding charging capabilities with charging speeds of less than an hour. The term ultra-fast charging has emerged, with a significant charging capability with a charging speed of less than 10 minutes [6].

The charging system for electric vehicles, especially electric motorcycles currently available, is classified as slow charging because it requires 3–4 hours to reach a full-charge state. The method used in the charging process can affect battery performance. The amount of charging current used affects the charging time and battery degradation rate [7]. The constant current and constant voltage or CC-CV charging method holds the current constant until the battery voltage reaches its maximum level. The charging current is reduced to maintain the battery voltage at its maximum [8]. This protocol is easy to implement and efficient when used with a battery management system (BMS) [9] and can prevent overcharging due to the constant voltage method [8].

In 2022, Jha et al. compared the charging time of Lithium-Ion batteries with the five-stage-based multistep constant current (MSCC) method, which provided a faster charging performance than the CC-CV method [10]. According to Nizam (2022), the use of fuzzy logic algorithms for the constant current process (CC-fuzzy) will speed up the charging process and reduce the temperature rise in the battery [11]. Several other studies have developed optimized charging methods to maintain maximum battery performance, such as employing artificial intelligence like particle swarm optimization algorithm on adaptive multistage constant current and constant voltage [12], to a combination of Fuzzy algorithms and Genetic algorithms [13]. However, optimizing the charging methods requires increased hardware capabilities. So, it will consume more significant costs for the implementation process.

In high power usage, many lithium-ion batteries are connected in series and parallel to achieve high voltage and capacity [14]. Experiments conducted by Li in 2021 show a comparison of battery charging capabilities between single batteries with batteries already assembled in pack form [15]. The constant current phase in the battery pack is reduced compared to a single battery due to the equilibrium management of the battery pack. In this study, we developed a fast charging system based on a DC-DC converter with a buck converter topology to charge a 48V battery with a capacity of 10.8 Ah. The type of buck converter used is a synchronous buck converter to get high power conversion efficiency.

* windhugriya@staff.uns.ac.id

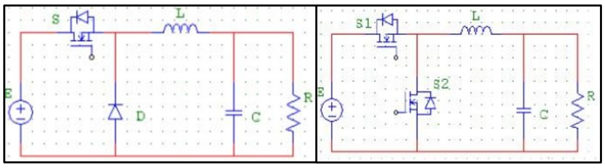

Fig. 1. Buck converter circuit diagram: nonsynchronous buck converter (left) and synchronous buck converter (right) [16]

2 Methods

2.1 Buck Converter

A buck converter is a device that reduces the voltage to a specific level by breaking down the input voltage through a switching device controlled by a pulse-width modulation (PWM) signal. Stabilizing the split voltage and current is achieved through inductors and output capacitors.

Fig. 1 shows the use of a diode to rectify the power. On the other side, Fig. 2 shows the replace the diode with low-side mosfet. The use of mosfet provides the benefit of a lower voltage drop than diodes. With the same current magnitude, the decrease in voltage drop will reduce power dissipation and increase efficiency.

2.2 CC-CV Charging Protocol

Constant current, constant voltage (CC-CV) is a charging protocol that consists of two primary operations, namely constant current (CC) and constant voltage (CV). The CC-CV protocol begins with the CC process until the battery voltage reaches the maximum voltage and then continues with the CV process until the charging current approaches zero.

The CC process provides a constant current to the battery. In a slow charging system, the charging current remains constant, ranging from 0.25 to 0.5 times the battery capacity. It is commonly called as 0.25C - 0.5C. While in the fast charging process, the amount of current given is 1C to 2C. During the CC process, the state of charge (SOC) value will increase linearly because the incoming current value is unchanged.

When the battery charging voltage has reached the predetermined maximum battery voltage (usually 3.65 V for a single cell of LiFePO4 battery), the current will reduced so that the charging voltage does not exceed its maximum voltage. This CV process helps to prevent overvoltage during the charging process by limiting the maximum charging voltage.

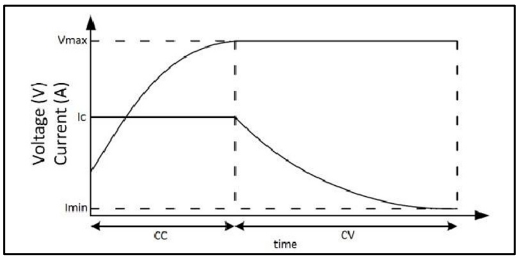

Fig. 2. CC-CV typical operation [17].

2.3 LiFePO4 Battery Pack

LiFePO4, also known as LFP batteries, has a nominal voltage of 3.2 V (V_{cell}), and the minimum and maximum voltages are 2.5 V and 3.65 V, respectively. The battery used in this battery pack is a 18650 cylindrical battery with a battery capacity per cell (C_{cell}) of 1800 mAh.

In the process of battery pack assembly, the batteries will be arranged in series and parallel to get the desired pack voltage (V_{pack}) and battery pack capacity (C_{pack}). The series arrangement is employed to obtain the desired battery pack voltage, while the parallel arrangement aims to increase the capacity of a larger battery pack. The equations (1) and (2) is used to calculate the number of battery cell in series and parallel.

$$V_{pack} = n_{series} \times V_{cell} \tag{1}$$

$$C_{pack} = n_{parallel} \times C_{cell} \tag{2}$$

The battery pack is designed by following the specifications specified in Table 1.

2.4 System Specifications

DC fast-charging is a system that converts high-voltage DC input into a battery pack's maximum voltage level. The DC fast-charging development process follows the hardware specification in Table 2.

Table 1. Lifepo4 Battery Pack Specifications

Parameter	Symbol	Value
Battery Pack Voltage	V_{pack}	48 V
Battery Pack Capacity	C_{pack}	10 Ah
Cells in Series	n_{series}	15
Cells in Parallel	$n_{parallel}$	6
Battery Pack Maximum Voltage	V_{max}	54,75 V
Battery Pack Minimum Voltage	V_{min}	37,5 V

Table 2. DC Fast Charging Specification

Parameter	Symbol	Value
Input Voltage	V_s	80 V – 100 V
Output Voltage	V_o	40 V – 60 V
Maximum Output Current	I_o	22 A
Switching Frequency	fsw	18 kHz
Inductance	L	400uH
Input Capacitor	C_{in}	2 × 470uF
Output Capacitor	C_{out}	2 × 470uF

3 Results And Discussions

Testing involved a 48V battery pack and a DC fast charging hardware across three current stages: 1C fast charging with a constant current of 10 A, 2C fast charging with a continuous constant current of 20 A, and 3C fast charging with a constant current of 30A. The charging process took place at a room temperature of 25 degrees Celsius.

3.1 Battery Pack Assembly

The battery pack assembly process configures batteries in 6 parallel and 15 series. It takes 90 battery cells in total. With this configuration, we obtain a battery pack with a nominal voltage of 48 V. Since the battery used has a capacity of 1800 mAh for one battery cell, the total capacity of the assembled battery pack is 10.8 Ah. The battery pack is also connected to the BMS to protect the battery from unwanted conditions.

3.2 DC Fast Charging Board

The design is mainly from buck converter topology with two 470uF capacitors at the start of the buck converter as a filter on the input high-voltage side of the buck converter. A diode was added at the output side after the output capacitor to create a single direction of current flow on the output side. There are 6 cm x 6 cm fan and heatsink on top of the mosfet to manage heat dissipation from the mosfet.

The microcontroller manages to control the PWM signal. Varying PWM values will give the result of different voltage output levels. The voltage difference between charger output and battery terminal voltage will determine the output current. In this situation, controlling the PWM signal will affect both the output voltage and the output current.

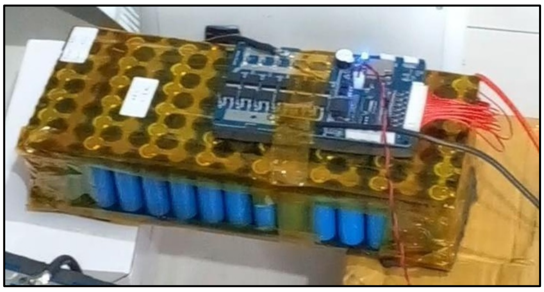

Fig. 3. LiFePO4 48 V 10.8 Ah Battery Pack

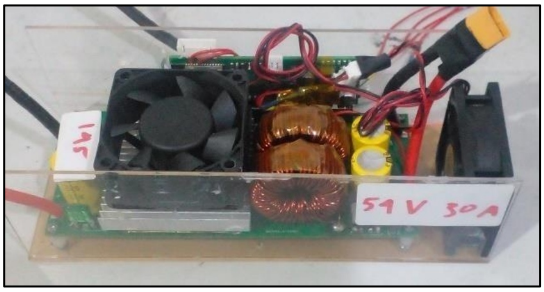

Fig. 4. DC Fast Charging Board

3.3 Fast Charging 1C Test

In this test, the output current setpoint for charging was limited to 10 A through the microcontroller program. The maximum voltage allowed is limited to 53 volts. Charging starts with the battery's SOC at 0%.

Fig. 5 shows a graphic of the voltage, current, and SOC of the battery pack at the 1C charging test. The charging time required to reach 50% SOC is about 33 minutes. And then, SOC 80% is achieved when the charging process has been running for 57 minutes. The battery fully charged at the 77th minute. Here, the constant current process takes only 16 minutes, and the remaining 61 minutes are for the CV phase.

In the charging process with a charging rate of 1C, the time required to reach the 100% SOC state still takes more than 1 hour because of the relatively long CV process. For charging time under 1-hour purposes, the charged battery pack capacity is only 80%.

3.4 Fast Charging 2C Test

The output current setpoint for this test is 20 A due to the higher charging rate. The maximum allowed charging voltage is 53 V and starts at SOC 0%

In Fig. 6, the total time needed to achieve a 100% SOC state is 43 minutes, with the detail of the charging time required to achieve 50% SOC and 80% SOC being 18 minutes and 30 minutes, respectively. The CC process lasts 18 minutes, while the CV phase takes about 25 minutes.

In this charging test, we can get a fully charged battery pack in under 1 hour, which takes about 43 minutes. Theoretically, 2C charging will give a fully charged battery pack at 30 minutes. But, because the CV needs a lower current, the charging time is extended.

3.5 Fast Charging 3C Test

From Fig. 7, 30 A of charging current is used along with the output voltage of 52 V. The maximum voltage setpoint is decreased by 1 V to avoid BMS cut-off due to an uneven voltage increase between cells in the battery pack.

The constant current process only lasted for 3 minutes, which is equivalent to 10% of the battery capacity. The charging current immediately drops to around 23 A because the battery pack voltage has reached the maximum setpoint. The process then continued with a constant voltage phase, which takes 37 minutes. In the 3C charging experiment, the SOC states of 50%, 80%, and 100% were reached at 15 minutes, 26 minutes, and 39 minutes, respectively.

3.6 Fast Charging Time Comparison

Fig 8. shows the charging time for each stage. The 1C charging process provides the longest charging time compared to the other two experiments. The amount of input power for charging contributes to its longer charging time. Increasing the charging power by two times from 1C will reduce the charging time by 44%.

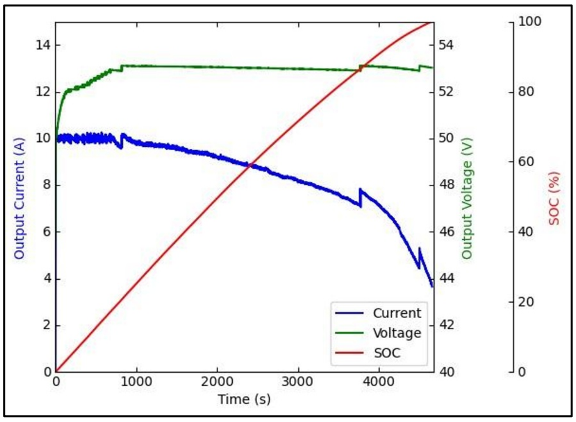

Fig. 5. Fast charging test with a charging rate of 1C.

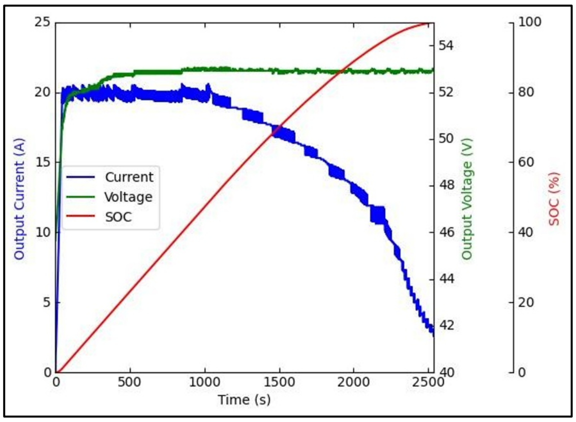

Fig. 6. Fast charging test with a charging rate of 2C.

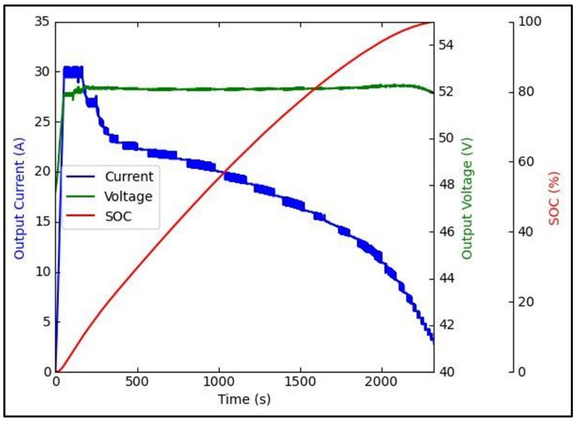

Fig. 7. Fast charging test with a charging rate of 3C.

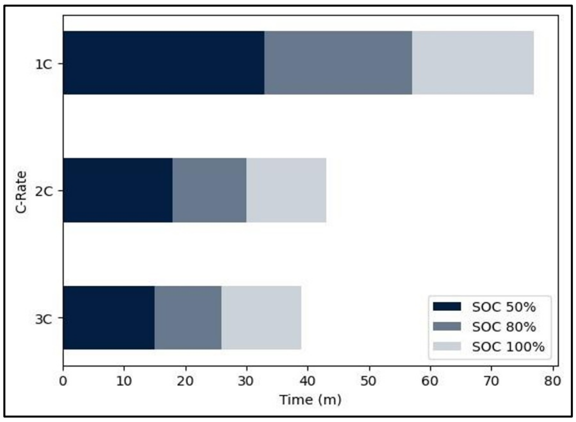

Fig. 8. Charging time comparison.

At the 3C charging test, the time difference is only about 4 minutes or 9.3% of the charging time with 2C. The compatibility of the battery pack to receive a higher charging rate contributes to this difference in charging time between 2C and 3C. The battery pack is not able to accept charging with a larger current. As seen in Fig. 7, the CC process time only lasts for 3 minutes or only 7% of the total charging time because the battery pack has reached its maximum voltage.

4 Conclusion

DC fast charging system is designed to charge 1C, 2C, and 3C with a maximum current of 30 A to a LiFePO4 battery pack with a nominal voltage of 48 V. DC fast charging system uses a synchronous buck converter topology and a constant current and constant voltage (CC-CV) charging protocol. PWM signals from the microcontroller regulate the current and voltage values for the battery charging process. From the tests, the 1C charging process provides a total charging time of 77 minutes, 43 minutes for 2C charging, and 39 minutes for charging with 3C power.

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