Evolution in Electrical and Electronic Engineering Vol. 4 No. 1 (2023) 644-653

EEEE

Homepage: http://publisher.uthm.edu.my/periodicals/index.php/eeee
e-ISSN : 2756-8458

Design of Lithium-Ion Battery Charger System with Automatic Voltage Regulator Feature

Amirul Alif Shuhariman[1], Asmarashid Ponniran[1]*

[1]Faculty of Electrical and Electronic Engineering,
University Tun Hussein Onn Malaysia, Batu Pahat, 86400, MALAYSIA

*Corresponding Author Designation

DOI: https://doi.org/10.30880/eeee.2023.04.01.077
Received 06 February 2023; Accepted 26 February 2023; Available online 30 April 2023

Abstract: In industrial locations, the need for dc power is crucial in the twenty-first century. The majority of applications need the dc power supply for functioning. Effective DC power is capable of controlling the electrical equipment properly. In this project, a rectifier and DC Buck converter are developed. The DC voltage is produced by the converter, which is get control by a microcontroller is represent the signal. PI controller is meant to alter the converters PI value in order to manage the output voltage of the buck converter. Using the MATLAB simulation application, the simulation circuit is created. Developing an experimental setup to validate simulation findings. Developing the buck converter circuit using MOSFET as the switching component. The microcontroller is utilized to run the PWM signal's programmed PI controller. In this project, passive cell balancing is used to ensure that four cells are charged to the same proportion. The modelling and experimental findings indicate that the output voltage of the buck converter have been regulated with the PI value in closed-loop system which provide the output voltage value of maximum, mean and minimum that equivalent to 16.96 V, 16.82 V and 16.66 V respectively. Thus, this proves that the research corresponding is successfully achieved because the output voltage value does not stray off from the desire value which equal to 16.8 V.

Keywords: DC to DC, Buck, PI controller, Closed-loop, Charging

1. Introduction

A buck converter is a device that takes a high-voltage DC input and transforms it into a low-voltage DC output. When powering the traction motor of an electric vehicle, a DC converter is typically employed. The converter has great acceleration control smoothness, efficiency, variable reaction speed, and dependability [1]. A DC converter may be either a buck, a boost, or a buck-boost. The DC output voltage is adjusted in response to the load attached to the terminal [2]. This Buck-topology enables an output voltage of down to 16.8 V. The output is coupled as a feedback circuit to the voltage monitor circuit, which usually focuses on the output voltage. Adjustments to duty cycles will be made to meet the needs of different load voltages.

Corresponding author: asmar@uthm.edu.my

The popularity of Lit-Ion batteries in portable electronic gadgets is well recognized. With the same size and weight, Lit-ion batteries can hold more energy than Ni-Cd batteries. Lit- Ion batteries are ideal for portable electronic applications because of their compact size, lightweight, and ability to be recharged [3]. Undercharged or overcharged Li-Ion batteries, on the other hand, have a significant impact on their life cycle. Because overcharging may harm the physical components of batteries and undercharging can limit their energy capacity, it's important to keep them charged [4]. Furthermore, Li-Ion batteries' most serious flaw is their lengthy charging time. Li-Ion batteries require a long time to charge to full capacity. As a result, this research proposes an accurate and charging charger to address the serious difficulties. The control of the proportional controller in addition to the control of the integral controller is employed in the proportional-integral (PI) controller. The combination of these two distinct controllers results in a controller that is more effective and does away with the drawbacks that are connected with each of the individual controllers [5].

This project will develop buck converter using voltage control system for battery charging. The voltage controller that uses in this project is PI controller in order to maintain the voltage output. The microprocessor generates the pulse width modulation (PWM) signals that regulate the output voltage. To measure the output voltages, we employed a battery load with varying voltage ratings. The MATLAB programmed was used to create the buck converter schematic. In this endeavor, the first encountered and then used the PI controller.

2. Methodology

This chapter will discuss the approach that will be used and the general flow of the project in order to accomplish the goal that has been set for this project. Within the scope of this research, an investigation of the behavior of a conventional converter will be carried out. The study is centered on the nature of the passive component in the rectifier and buck converter in order to get a better understanding of the problems that are encountered in conventional circuits, which include the complicated size of the converter and the voltage stress that is placed on the semiconductor device. The design and mode of operation for a conventional that has been simulated by utilizing Simulink Software are both presented in this chapter as well.

2.1 Operation of The System

In this design, two converters in this design will merge two circuits into one. In order to construct a battery charger, this project's combo converter combines a rectifier and a buck converter. Utilizing a PI controller, voltage is controlled both internally and externally depending on feedback information. In this project, passive cell balancing is used to regulate the battery's charge. Since this project used four 4-cell lithium-ion batteries connected in series, the passive cell balancing will regulate how much each cell charges, ensuring that in a given amount of time every percentage of the battery has the same state of charge and is charging at the same rate. Figure 1 shows the system flowchart.

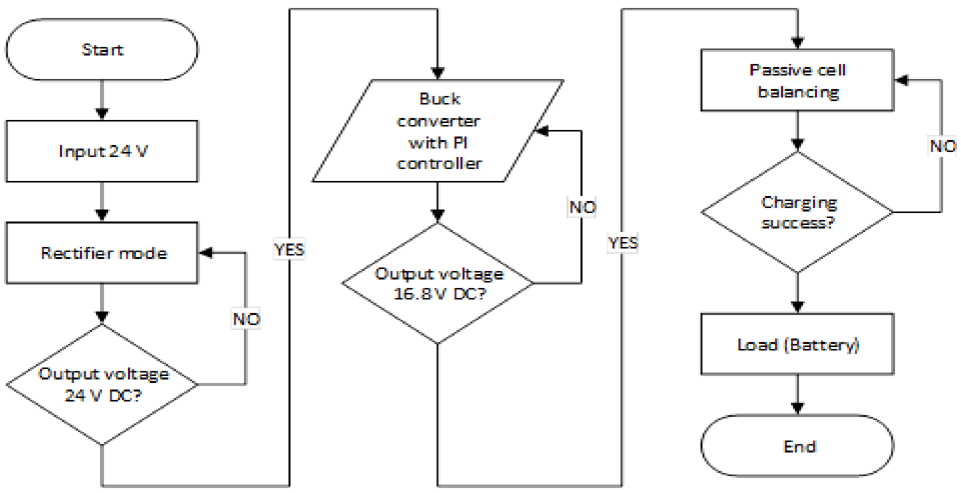

Figure 1: System Flowchart

2.2 System Block Diagram

Figure 2 shows the block diagram and model of combination rectifier and buck converter with applied passive cell balancing with constant voltage feature for battery charger application. The charging system and combination of two converter were created and applied to charging on the battery charger, as previously indicated. The rectifier and buck converter will play the primary role in this project's power converter design. The 230-240 V AC power supply from the socket outlet will be converted to DC by the rectifier. In order to lower output ripple voltage, a filter is placed after the rectifier. Next, it will be converted to a voltage of 16.8 volts by the buck converter before charging the battery pack. Battery controller and microcontroller are used as the PI controller in a closed loop system, which compares feedback values with output values while implementing the charging technique. Cell balancing will control the output of voltage from converter to the battery [6].

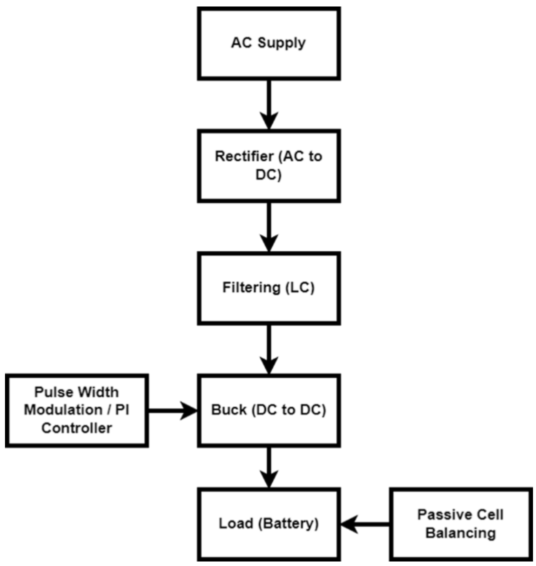

Figure 2: Block Diagram of Design Closed-loop AC-DC Buck Converter

2.3 System Design Circuit

Figure 3 presents the Closed-loop AC to DC Converter with Passive Cell Balancing in Simulation. The simulation model that was created with the help of the Simulink application. This model illustrates an AC-DC buck converter with a closed-loop circuit and a battery operating as the load. The converter that is being used in this simulation is demonstrating a charging system since rate of output voltage is constant that controller by setpoint of PI controller. The design of the simulation circuit that is currently being built by parameter on Table 1 parameters as its base. These parameters will serve as the foundation for the design. This foundation is going to support the structure that is going to be built. This model illustrates a Closed-loop Circuit with implement of passive cell balancing. When charging, the cell balancing circuit will be sent to the appropriate battery module. The voltage differential between individual cells triggers the balancing process.

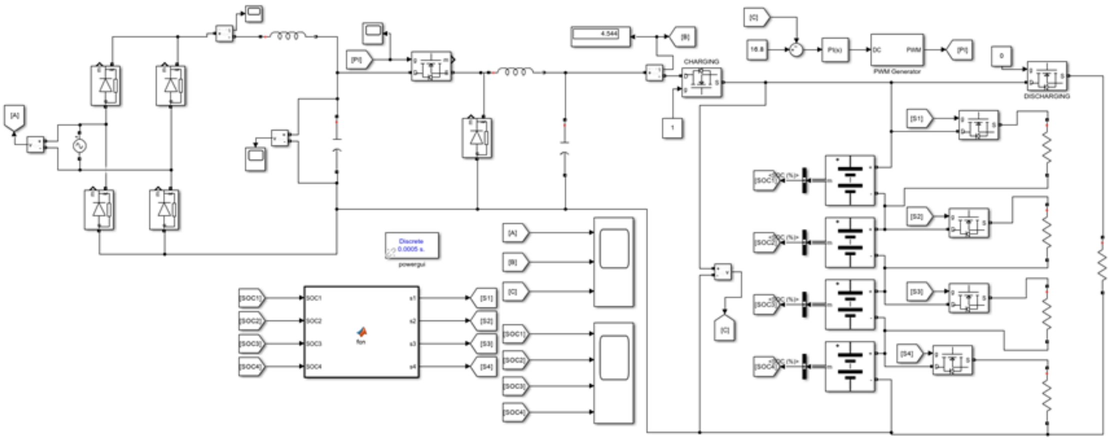

Figure 3: Closed-loop AC to DC Converter with Passive Cell Balancing in Simulation

Table 1: Parameter for Integration Rectifier and Buck Converter with Battery as Load

Specification	Ratings
AC Input voltage, *Vac*	240 V
Output Voltage, *Vout*	16.8 V
Inductor, *L1*	150 mH
Inductor, *L2*	50 mH
Capacitor, *C1*	1 mF
Capacitor, *C2*	1 mF
Setpoint	16.8
Proportional, *P*	7
Integral, *I*	1.5
Lit-ion Battery	3.7 V (2 Ah)

Table 1 shows the parameter for integration rectifier and buck converter. The design shows integrated rectifier converter with buck converter can be seen in Figure 3. The Component that consists in this circuits is AC supply, Diode, Inductor, Capacitance, MOSFET, Resistor, and PI controller and Lit-ion battery. All component that consists in this structure are used to simulate based on conventional and closed-loop structure method. the purpose of the project that is building a battery charger by employing a power converter is to construct an integration between rectifiers and buck converters that will allow for the charging of lithium-ion batteries. The rating of inductor and capacitor that show in table have been choose in order to reduce ripple since small rating reduce small amount of output ripple.

2.4 Specification and Rates

Table 2 shows the parameter PWM and PI controller for buck. The parameter shows different controller of buck converter which is pulse width modulation and PI controller. The open-loop and closed-loop of buck converter is use in order to constant output voltage so it can charge the battery at maximum voltage of the battery. The open-loop or conventional control the output voltage by optimizing the PWM, while closed-loop is controlled by PI at setpoint as a reference. All component that consists in this table are used to simulate based on conventional and closed-loop structure method before applying into integration between rectifiers and buck converters that will allow for the charging of lithium-ion batteries. Rate of PI has been set based on standard value that commonly used. Rate of conventional has been calculated using basic calculation for buck converter.

Table 1: Parameter PWM and PI controller for Buck Converter

Specification	PWM Rate	PI Rate
Duty Cycle	0.718 / 71.8%	
Input Voltage	24 V	24 V
Output Voltage	16.8 V	16.8 V
Frequency	50 kHz	
Inductor	22.5 uH	50 mH
Capacitor	133 uF	47 0uF
Resistor	6 ohms	6 ohms
P variable		7
I variable		1.5

The duty ratio for continuous-current operation

$$D = \frac{Vo}{Vs} = \frac{16.8}{24} = 0.7 \qquad \text{(Eq.1)}$$

For continuous-current operation, the switching frequency and inductor must be chosen. Let's randomly set the switching frequency to 50 kHz, which is below the audible range while still being low enough to minimize power lost in the process.

$$Lmin = \frac{(1-D)R}{2f} = \frac{(1-0.7)6}{2(50000)} = 18\ \mu H \qquad \text{(Eq.2)}$$

The inductor that been considered is 25% larger than the minimum to ensure that inductor current is continuous:

$$L = 1.25(Lmin) = (1.25)(18\mu H) = 22.5\mu H \quad \text{(Eq.3)}$$

$$IL = \frac{Vo}{R} = \frac{16.8\,V}{6} = 2.8\ A \qquad \text{(Eq.4)}$$

Average inductor current and the change in current,

$$\Delta ILmin = \left(\frac{Vs-Vo}{L}\right)DT = \left(\frac{24V-16.8\,V}{22.5\ \mu H}\right)(0.7)\left(\frac{1}{50\ kHz}\right) = 4.48A \qquad \text{(Eq.5)}$$

The maximum and minimum inductor currents,

$$Imax = IL + \frac{\Delta iL}{2} = 2.8\ A + 2.24\ A = 5.04\ A \qquad \text{(Eq.6)}$$

$$Imin = IL - \frac{\Delta iL}{2} = 2.8\ A - 2.24\ A = 0.56\ A \qquad \text{(Eq. 7)}$$

The capacitor is selected,

$$C = \frac{(1-D)R}{8L(\frac{\Delta Vo}{Vo})f^2} = \frac{(1-0.7)}{8(22.5\ \mu H)(0.005)(50\ kHz)^2} = 133\ \mu F$$

2.5 Passive Cell Balancing Design

Figure 4 shows Passive cell balancing circuit which is used to balances battery cells and protects battery packs during charging. This project will test 4 Lit-Ion batteries in series, which may generate unbalanced. One or more cells reach maximum charge before the others. A resistor dissipates the energy of the series pack's highest-voltage cell in this passive cell balancing system. This BMS will use constant voltage to charge all batteries to 100% state of charge (SoC) in balance.

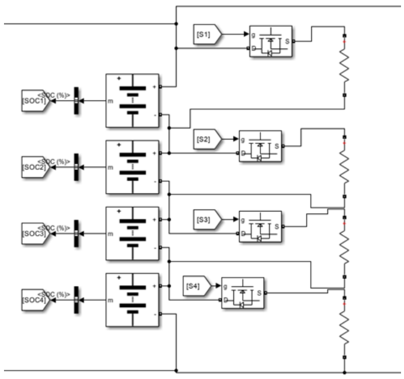

Figure 4: Passive Cell Balancing Circuit

3. Results and Discussion

The simulations have been built with the help of the Simulink programmed. This section will cover all of the simulation findings and explain them in detail. The simulation has been constructed with the parameters that were discussed in the part before. The simulation of rectifier and buck converter with PI controller circuits is compared in order to examine the findings and to verify the closed-loop circuit in order to accomplish charging approach. This comparison is made in order to achieve both of these goals. This section will illustrate the waveform of close-loop and the switching signal, also known as pulse-width modulation (PWM), as well as the current flowing through the input side of the converter circuit, as well as the input voltage and output voltage.

3.1 Conventional Voltage of Rectifier with LC Filtering

Figure 5 shows the rectifier's waveform after the filter has been applied to the diode-based rectifier's output. The filter was put in place to remove or help to reduce ripple voltage on the waveform so that a pure DC signal could be analyzed. The filter's elimination functionality, where it prevents undesired signals from entering the circuit. The final product is an improved DC signal quality due to the filtering process.

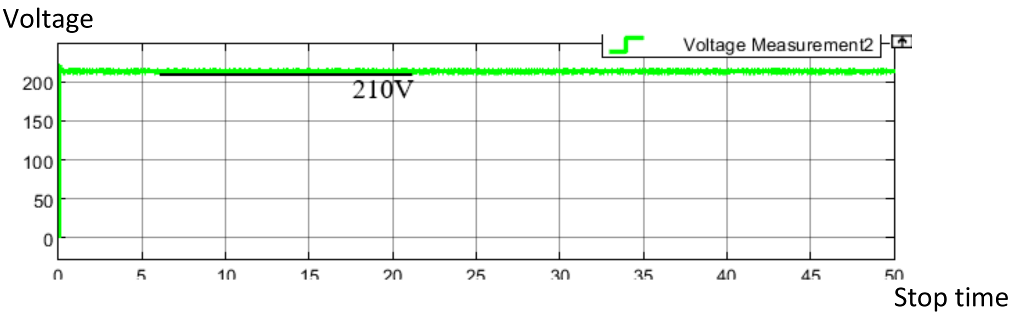

Figure 5: Waveform of Rectifier with LC Filter.

3.1.1 Output Voltage and Current of Conventional DC Buck Converter

In this part, the output voltage and current waveforms that are generated by the conventional buck converter circuit are noted down and discussed which can be seen in Figure 6. In order to demonstrate that the principle of the buck converter is correct, which is that the output voltage must be lower than the input voltage based on the specified buck ratio, this will be done. The waveforms of the output voltage of a DC buck converter are 16.8 V while the input is 24 V.

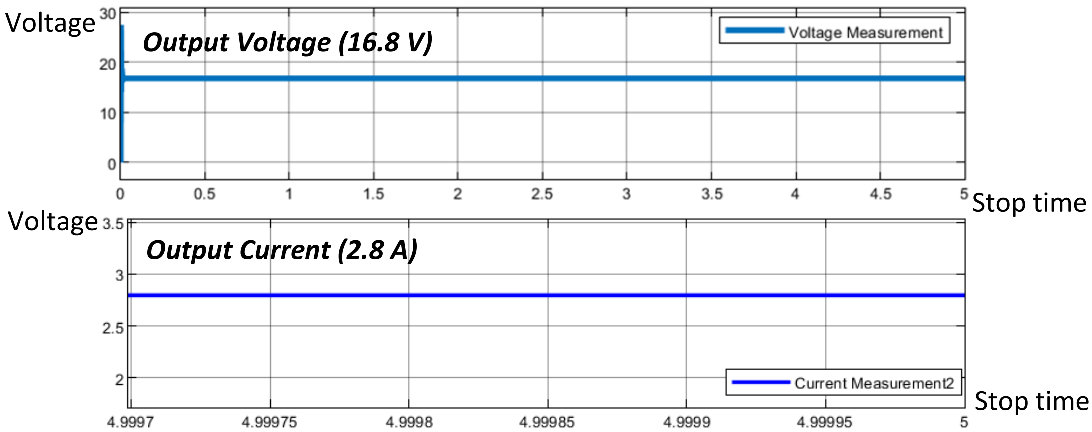

Figure 6: Voltage and Current Output Measurement of Conventional DC Buck Converter

Table 3 shows voltage and current output measurement of conventional DC buck converter. There six different rate of the output voltage and current with consists of maximum, minimum, peak to peak, mean, median and RMS which is shown in table below.

Table 3: Voltage and Current Output Measurement of Conventional DC Buck Converter

	Voltage Measurement	Current Measurement
Maximum	28.21 V	2.797 A
Minimum	0.0014 V	2.797 A
Peak to Peak	28.20 V	0.061 mA
Mean	16.80 V	2.797 A
Median	16.21 V	2.797 A
RMS	16.80 V	2.797 A

3.2 Output Voltage and Current of Closed-loop DC Buck Converter

The input and output voltage waveforms that are generated by the closed-loop DC buck converter circuit are analyzed and discussed. Additionally, in this section, the input and output voltage waveforms that are generated by the closed-loop buck converter circuit are stepped down and discussed. This is going to be done in order to demonstrate that the principle of the buck converter is correct, which is that the output voltage must be lower than the input voltage based on the specified buck ratio and rate of PI controller. Figure 7 illustrates the waveforms that are produced at the output voltage and current of a closed-loop DC buck converter.

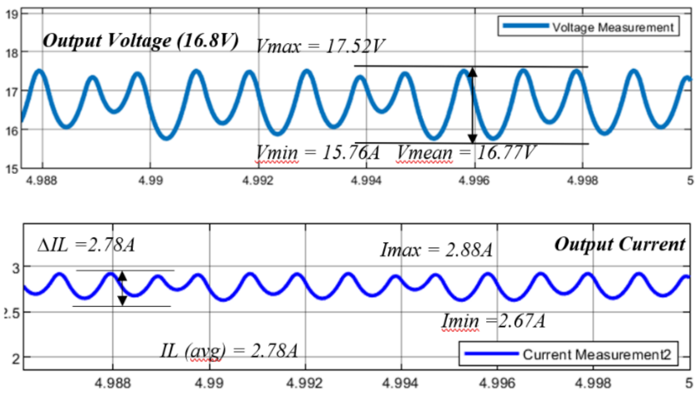

Figure 7: Output Voltage and Current for Closed-loop Buck Converter.

Table 4 shows voltage and current output measurement of closed-loop DC buck converter. There six different rate of the output voltage and current with consists of maximum, minimum, peak to peak, mean, median and RMS which is shown in table below.

Table 4: Voltage and Current Output Measurement of Closed-loop DC-DC Buck Converter

	Voltage Measurement	Current Measurement
Maximum	17.52 V	2.920 A
Minimum	15.76 V	2.626 A
Peak to Peak	1.76 V	0.293 A
Mean	16.77 V	2.792 A
Median	16.84 V	2.802 A
RMS	16.78 V	2.794 A

3.3 Closed-loop AC to DC buck converter with 4 cell lit-ion Battery with passive cell balancing

Figure 8 shows the waveform of the voltage and current output by a closed-loop AC to DC buck converter that is being charged into the battery. Due to the use of an inductor with a rating of 50 mH, the ripple of the output current has been significantly decreased. Since the system is now operating in a steady condition, the output current will be flowing in a continuous mode. in this operation, where the rate of output voltage is constant at maximum voltage of 4 cell battery in order to accomplish the charging.

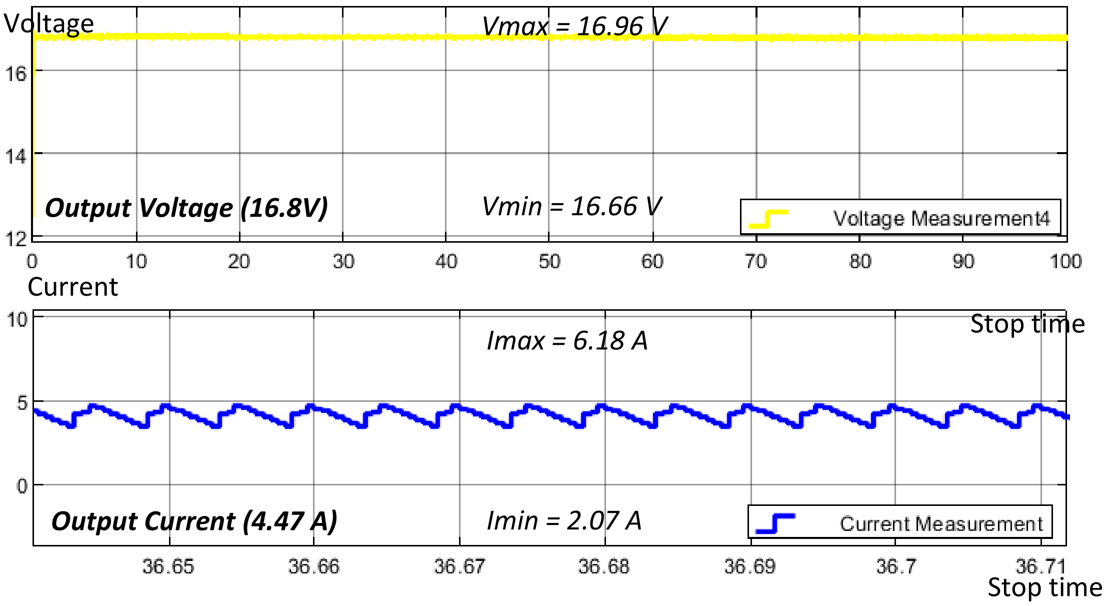

Figure 8: Waveform of Output Voltage and Current for Closed-loop Circuit Converter with lit-ion Battery with Passive Cell Balancing

Table 5 shows voltage and current output measurement of closed-loop AC to DC buck converter with 4 cell lit-ion Battery with passive cell balancing. There six different rate of the output voltage and current with consists of maximum, minimum, peak to peak, mean, median and RMS which is shown in this table.

Table 5: Output Voltage and Current of Closed-loop Circuit Converter with lit-ion Battery

	Voltage Measurement	Current Measurement
Maximum	16.96 V	6.18 A
Minimum	16.66 V	2.07 A
Peak to Peak	0.31 V	4.12 A
Mean	16.82 V	4.38 A
Median	16.83 V	2.797 A
RMS	16.82 V	2.797 A

The percentage of state-of-charge by a four-cell battery is shown in Figure 9. Running the simulation of a closed-loop AC to DC buck converter that has been developed previously makes it clear that charging is actually happening. The state of charge (SoC) of each battery has set differently in order to achieve the balancing of 4 battery cell that been set it set to 60%, 62%, 64%, 65%. The waveform displays that all four batteries charging at the same SoC (%) when it reaches certain time. This happens cause of the use of a passive cell balancing that applied to the battery, which controls the charging of a four-cell battery. The waveform demonstrates that the SoC (%) is increasing in same percentage when all battery reaches certain time.

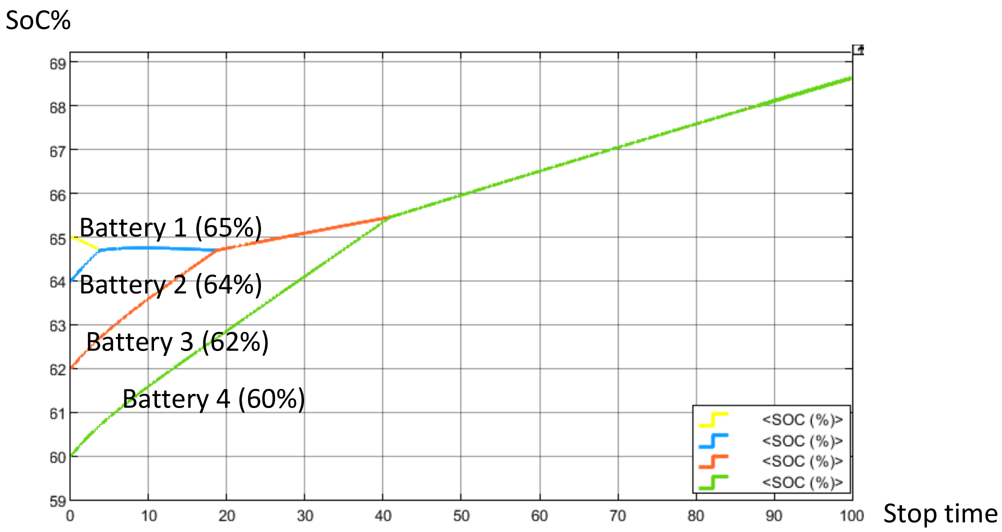

Figure 9: Waveform of State of Charge of 4-cell Lit-Ion Battery with Passive Cell Balancing

4. Conclusion

Overall, in this research, the goals of the research as well as the actual outcomes and discoveries are discussed and analyzed. It is to analyses whether the output voltage and current of the converter circuit can remain constant and charging. The objective of this project is to design and model of combination rectifier and buck converter with charging feature for battery, to design and model passive cell balancing on lithium-ion battery cell for stability and to develop for lithium-ion battery charger low power prototype of the buck converter circuit. In view of this, analysis of the two-combination converter circuit with PI controller has been carried out. This is done so that the voltage can be maintained at a constant and the integrated circuit converter may be charging efficiency. Also, passive cell balancing is done so the battery can charge in same state of charge.

Acknowledgement

The authors would like to thank the Faculty of Electrical and Electronic Engineering, University Tun Hussein Onn Malaysia for its support.

References

[1] Haque, M. R., & Razzak, M. A. (2021). A buck converter-based battery charging controller for electric vehicles using modified pi control system. 2021 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS). https://doi.org/10.1109/iemtronics52119.2021.9422646

[2] Faisal H.Khan, Leon M.Tolbert and William E.Web, "Hybrid Electric Vehicle Power Management Solutions based on Isolated and Non-Isolated Configurations of Multilevel Modular Capacitor Clamped Converter," IEEE Transactions on Industrial Electronics, Vol. 56, No.8, pp. 3679-3095 August 2009.

[3] Dung, L.-R., Chen, C.-E., & Yuan, H.-F. (2016). A robust, intelligent Charger for aging lithium batteries. 2016 IEEE 25th International Symposium on Industrial Electronics (ISIE). https://doi.org/10.1109/isie.2016.7744901

[4] Butt, Y. (2013). Lithium-Ion Batteries. New York Institute of Technology.

[5] says, B. R. R. L., & Lingampalli, B. R. R. (2020, January 11). What is proportional integral (PI) controller. Electronics Coach. Retrieved January 28, 2023, from https://electronicscoach.com/proportional-integral-controller.html

[6] Samaddar, N., Senthil Kumar, N., & Jayapragash, R. (2020). Passive cell balancing of Li-ion batteries used for automotive applications. Journal of Physics: Conference Series, 1716(1), 012005. https://doi.org/10.1088/1742-6596/1716/1/012005