Evolution in Electrical and Electronic Engineering Vol. 2 No. 2 (2021) 458-466

EEEE

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

Comparative Analysis of the Battery Charging System using Digital and PI Controller

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DOI: https://doi.org/10.30880/eeee.2021.02.02.055
Received 17 July 2021; Accepted 08 September 2021; Available online 30 October 2021

Abstract: Lithium-ion batteries are growing in popularity due to increasing demand and higher energy density; majorly contributed by the ever-advancing technology of portable devices and electric vehicles. A battery charger, or voltage regulator, which is crucial for charging and discharging, therefore must be specifically designed to prevent damages. This study is concerned with designing a digitally controlled charging system using a DC-DC boost converter, which is able to operate with a wide range of input voltage with specific output voltage. All the critical parameters for the proposed design components based on 100kHz switching frequency had been calculated and modeled using MATLAB/Simulink software. Several PI parameters had also been applied in order to verify the effectiveness of the model. The PI controller was simulated with different K_p and K_i, and the results had been analyzed in detail. The digital controller was programmed using Field Programmable Logic Array using Quartus II software. The results showed that with K_p =0.0009 and K_i =11.4 gave better performance than other parameters, with a rise time of 200.45μs, overshoot -1.503%, settling time of 10.40ms with an output voltage ripple less than 1%. Finally, A digital controller, Altera DE2-70 board with parallel 8-bit ADC, had been used to verify the performance of the proposed digital controller.

Keywords: Battery Charging System, PI Controller, DC-DC Boost Converter

1. Introduction

Nowadays, batteries are becoming even more essential in the world of technology as energy storage in portable devices such as laptops and smartphones. Batteries are a series of one or more cells whose chemical reactions produce electron flow in a circuit. Batteries are undeniably the best storage option for electrical energy storage [1]. In response to the demand and need for greater energy density, lithium-ion batteries are increasing rapidly in terms of their usage in portable devices [2]. Accordingly, Li-ion battery charger needs to be designed for optimum charge method or technique to prolong the Li-ion battery's lifespan. Critical components such as inductor and capacitor also need to be clarified at early stage of the development phase.

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Charging a battery without using any interface devices such as a converter or inverter will damage and shorten the battery life because the charging voltage or current is not regulated [3]. Among DC-DC converters, one of the common topologies in developing battery chargers is flyback topology. This topology basically focuses on simplicity of the circuit structure, ease of operation, and fewer switching devices, compared to other topologies. Despite that, there are drawbacks, such as flipping losses from the switch and reverse losses from diode recovery [4]. A DC-DC boost converter has a simple circuit structure, more straightforward operation, small number of switching devices, and high efficiency, which can be controlled using various methods to fulfill the battery charger operating specification.

Digital controller such as Altera DE2-70 can be used to control the circuit as it can be programmed through Quartus II software, which supports several types of programming language such as Verilog HDL, Very High Description Language (VHDL), Altera Hardware Description Language (AHDL), and schematic design entry[5]–[7]. An analog to digital converter (ADC), which functions as an input converter that discerns and identifies an analog signal in the digital domain, is necessary for a digital control to process the signal. For closed-loop realization, Proportional Integral (PI) controller has become a more preferable option for its excellent performance and ease of control. Despite these advantages, there are several drawbacks of PI controller, which are the undesirable overshoot and vulnerability to K_p and K_i controller gains [8].

This paper proposes the use of a boost converter as a battery charger circuit. All the critical parameters are calculated based on related equations. This project aims to design a battery charger system with an FPGA-based controller, along with parallel 8-bit ADC. A simulation for the battery with PI controller using MATLAB/Simulink software is also a highlight in this study to find the optimal system stability.

2. Circuit configuration and Methods

2.1 DC-DC boost converter

The boost converter critical component parameters are calculated based on related formulas. In order to quantify the value of inductance and capacitance, parameters such as input and output voltage, switching frequency, and duty cycle are set fixed. Through calculation, the inductor current was considered to be limited to 4A since the nominal discharge current of the 10Ah battery is 4.347A. The inductance was choosen to be much greater than calculated value to ensure that the circuit would operate in continuous conduction mode (CCM). Table 1 summarizes estimated components parameter for the proposed battery charger.

Table 1: Calculated Value Parameter

Parameters	Value
Resistor, $\boldsymbol{R}$	12Ω
Maximum output current, $\boldsymbol{I_{omax}}$	2A
Minimum inductor value, $\boldsymbol{L_{min}}$	$15\mu H$
Chosen inductor value, $\boldsymbol{L}$	$100\mu H$
Maximum inductor current, $\boldsymbol{I_{L(\max)}}$	4.3A
Minimum inductor current, $\boldsymbol{I_{L(\min)}}$	3.7A
Inductor current change, $\Delta\boldsymbol{I_L}$	0.3A
Capacitor value, $\boldsymbol{C}$	$41.67\mu F$
Chosen capacitor value, $\boldsymbol{C_C}$	$100\mu F$

2.2 Circuit Simulation using MATLAB/Simulink software

MATLAB/Simulink software was used to model the proposed battery charger. Figure 1 shows the open-loop DC-DC boost converter, while Figure 2 shows DC-DC boost converter with PI controller using MATLAB/Simulink software.

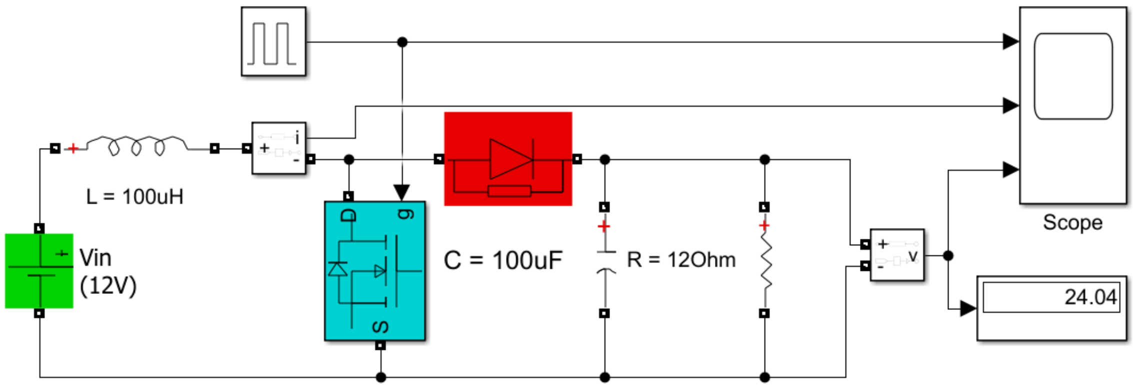


Figure 1: Open-loop system for boost converter design using MATLAB/Simulink software

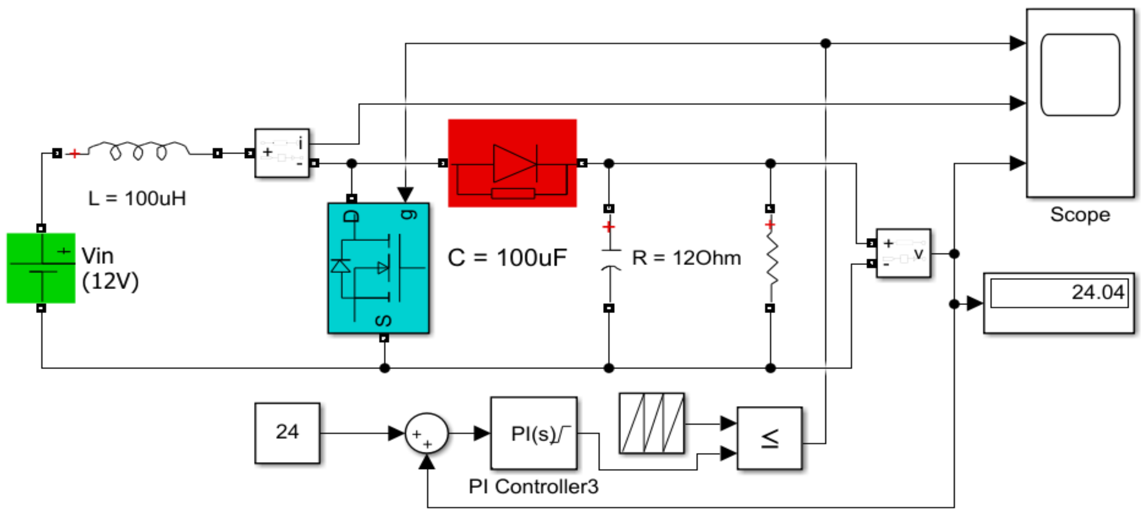


Figure 2: PI controller system for boost converter design using MATLAB/Simulink software

2.3 PWM generator using Quartus II software

The Pulse-Width-Modulated (PWM) generator for digital controller was written in VHDL (*.vhd), and then converted to a block diagram (*.bdf). Figure 3 shows the digital controller block diagram (*.bdf), while Figure 4 shows the Analog-to-Digital converter control diagram (*.bdf), designed using Quartus II software, which contains the functions *altpll*, *lpm_counter*, and *comparator*. The altpll was used to adjust the phase generated signal to match the phase of input signal. In this case, altpll was used to change the frequency of the clock inputs from 50MHz to 25MHz in order to generate a 100kHz switching frequency by setting the lpm_counter modulus to 255. A comparator was used to generate a PWM waveform with an inverse duty cycle that would function to compare the outputs of the lpm_counter and ADC. Due to the inverse PWM waveform generated, NOT gate was used for inverting purposes. An ADC was used to transform analog waveform feedback output voltage from a DC-DC boost converter. The analog signals must be changed to the digital form for the digital controller to compare it with the desired reference voltage.

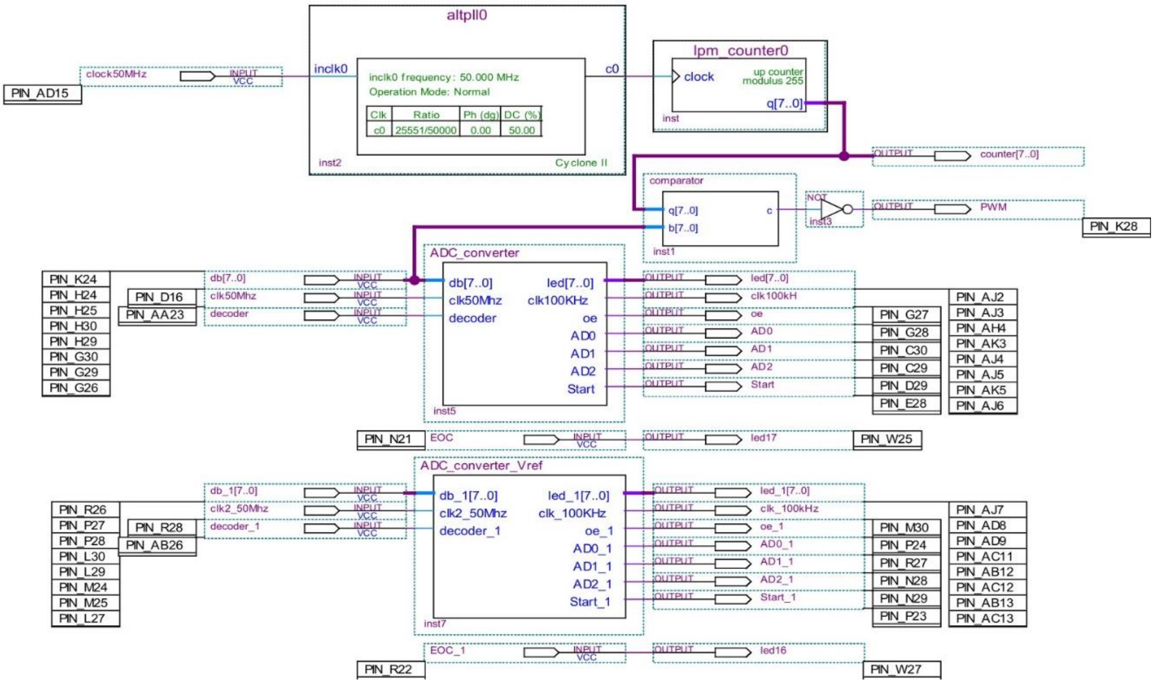


Figure 3: Digital controller block diagram (*.bdf)

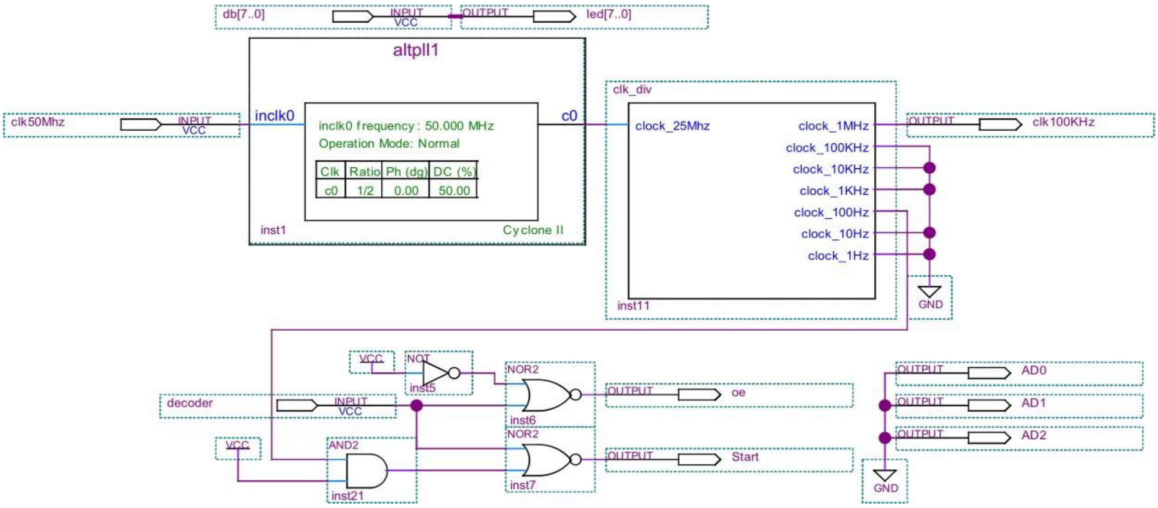


Figure 4: Analog-to-Digital converter control diagram (*bdf)

2.4 Hardware design and implementation

The configuration of this circuit consists of Altera DE2-70 board as controller, ADC0808/ADC0809 8-Bit µPcompatible A/D converters with 8-channel multiplexer to convert analog signal into digital signal, gate driver, variable knob, and voltage divider circuit to act as a level shifter from 24Vto 5V. The gate driver output is connected to the MOSFET terminal and the input of the voltage divider circuit is connected to the boost converter output. Figure 5 shows the hardware implementation of digital controlled by using FPGA controller and ADC for boost converter.

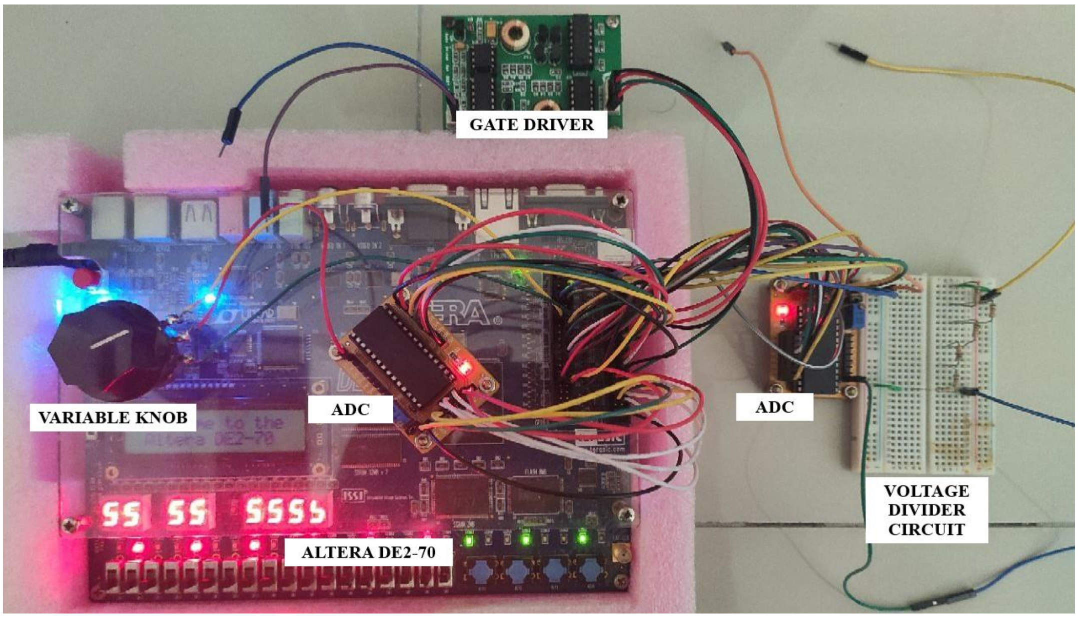


Figure 5: Hardware implementation of digital controlled by using FPGA controller and ADC

3. Results and Discussion

3.1 Open-loop boost converter

The output of the open-loop boost converter was established via a MATLAB/Simulink simulation. Simulation was conducted using different duty cycles, ranging between 0.1 to 0.8, to observe the output voltage and current ripple behavior. From the simulation result, using duty cycle of 0.5, the output voltage was around 24V, and the maximum inductor currents were at 4.323A and 3.723A for minimum inductor current.The open-loop output voltage response with duty cycle 0.5 gave faster response as its rise time was 101.762µs with settling time, 19.722ms. However, the open-loop system had a significant disadvantage in its overshoot. This system had 145.547% overshoot, which is not desirable in battery charging applications as it can affect the battery lifetime. Figure 6 shows the waveform of open-loop boost converter with 0.5 duty cycle, while Figure 7 shows the open-loop output voltage response waveform obtained from MATLAB/Simulink simulation.

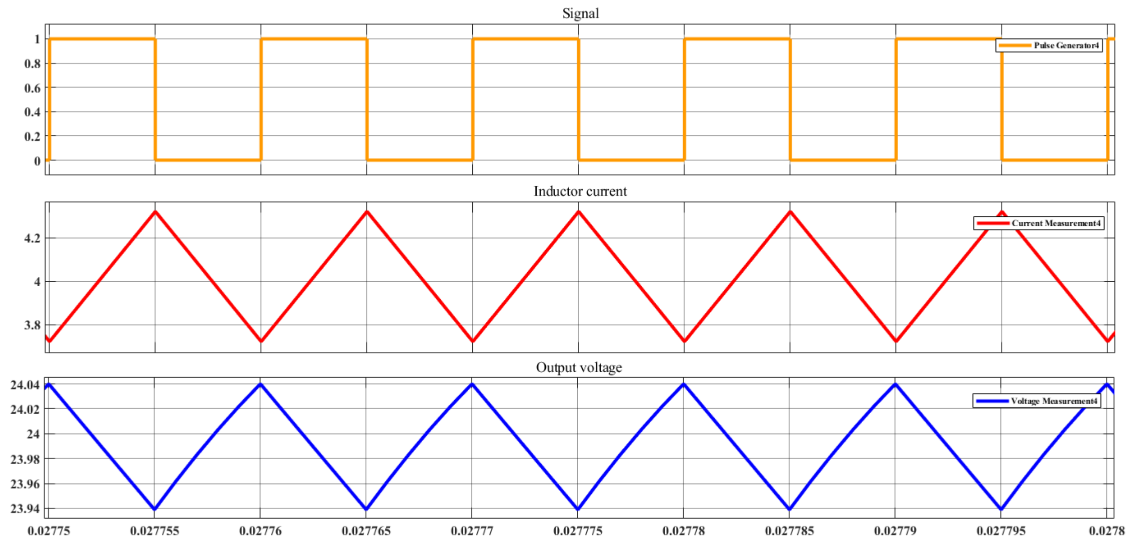


Figure 6: Waveform obtained from MATLAB/Simulink simulation for open-loop boost converter with 0.5 duty cycle

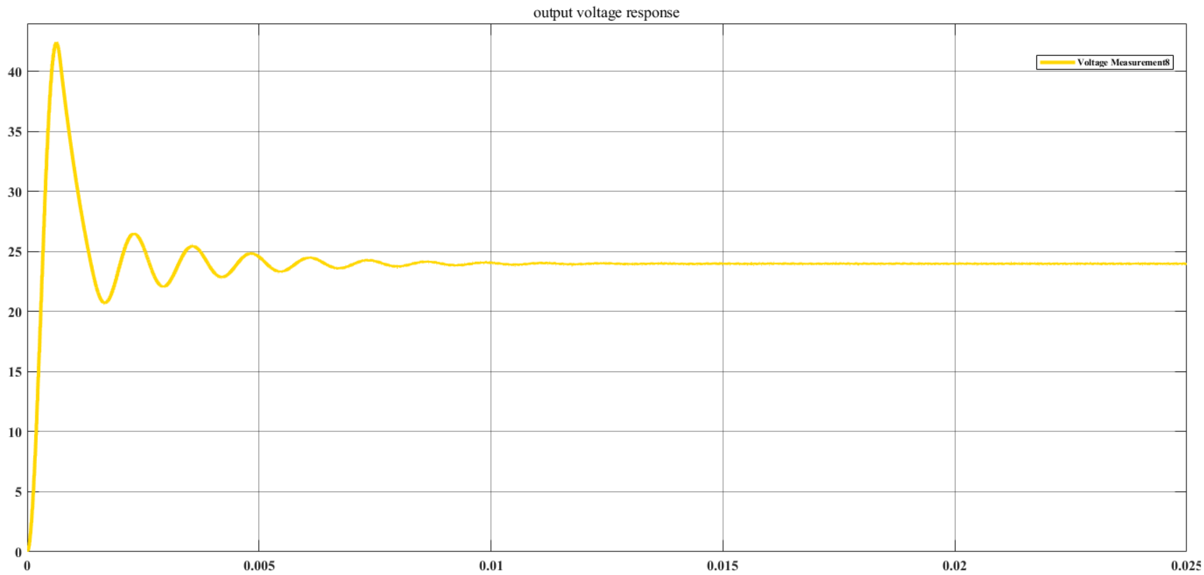


Figure 7: Open-loop output voltage response waveform obtained from MATLAB/Simulink

3.2 Boost converter with PI controller

The implementation of PI controller in boost converter is to control the output voltage to be close to the desired output and improve the response of the output itself. Table 2 shows the system performance in terms of rise time, settling time, and overshoot. All the are tuned manually with different tuning parameter combinations until acceptable results are achieved. Figure 8 illustrates the output voltage response waveform obtained from MATLAB/Simulink simulation for each system.

Table 2: System performance

	K_p	K_i	Rise time (µs)	Overshoot (%)	Settling time (ms)
System 1	0.01	7	183.308	8.152	19.559
System 2	0.0009	11.4	200.454	-1.503	10.400
System 3	0.0001	14.5	202.444	-0.385	11.081

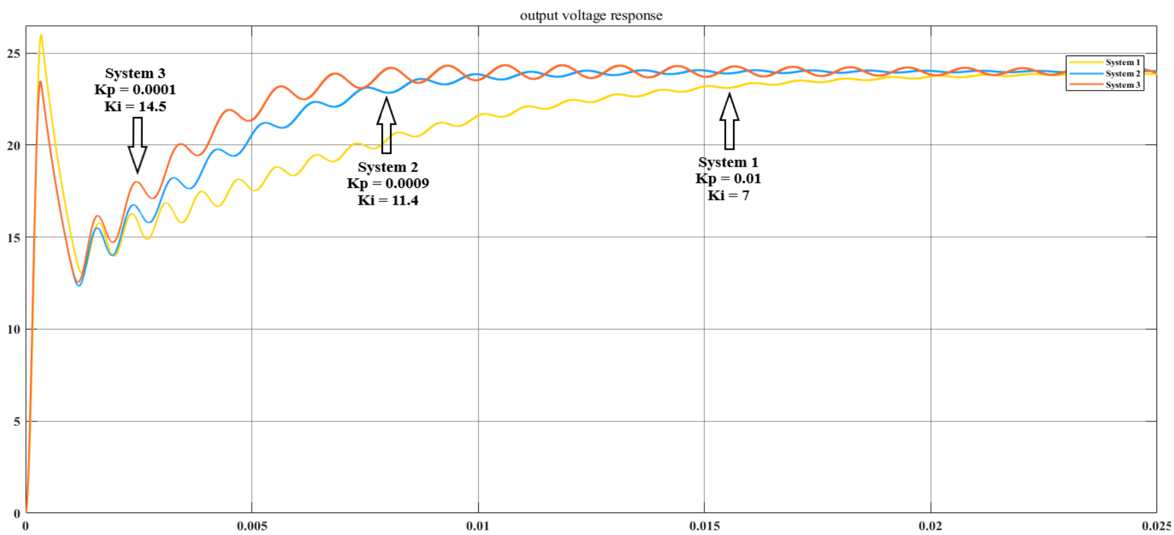


Figure 8: Output voltage response waveform obtained from MATLAB/Simulink simulation for each system

As shown in Table 2, even though system 2 had a slower rise time than system 1, it seemed to have greater performance when compared to system 1 and system 3. System 2 also had the fastest overshoot and settling time. When comparing an open-loop system to a PI control system, the open-loop system had a greater overshoot. In comparison, the PI control system had a lower overshoot, despite the fact that the open-loop system had a faster rise time. The PI control system had a shorter settling time than the open-loop control system in terms of steady-state. Other than analyzing the output response, the boost converter performance had also been analyzed in terms of the output voltage ripple. Table 3 shows the output voltage ripple between the open-loop system and PI control system. Note that the smaller output voltage ripple represents a better performance of the system, even though the difference between the ripple of open-loop system and PI control system 2 is just 0.001%.

Table 3: Output voltage ripple between open-loop system and PI control system

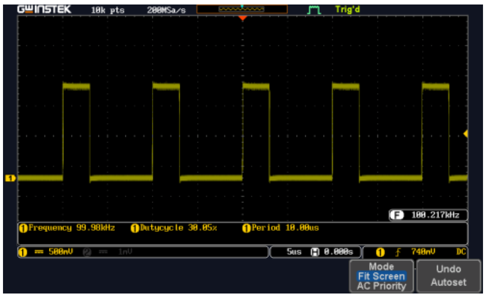
System	V_{in}	V_{ref}	Output voltage ripple (%)
Open-loop	12V	24V	0.417
System 1			0.458
System 2			0.416
System 3			0.416

3.3 Digital PWM signal generated from Altera DE2-70

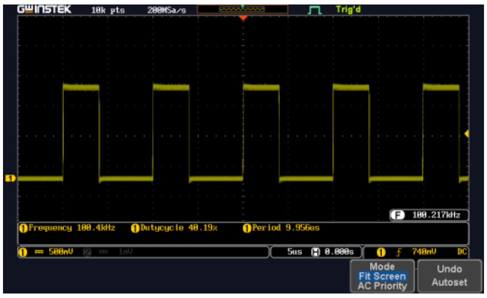
Quartus II structure programming provides a multiplatform plan condition that adapts to unique structure requirements. This software uses VHDL language, which then can be converted into block diagram file (.bdf). PWM signal was used to control the amount of current that flowed into the device, by pulsing the DC current and altering the amount of time when each pulse stayed on to manage the boost converter's output. Figure 9 shows the PWM signal generated by Altera DE2-70 with a duty cycle of 0.1 to 0.8.

(a) Duty cycle 0.1

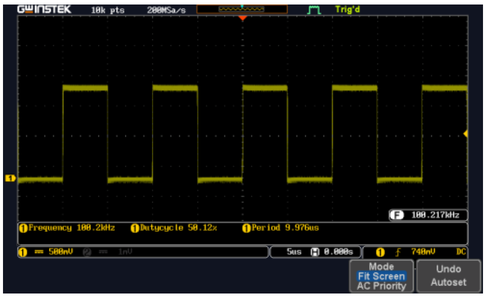
(b) Duty cycle 0.2



(c) Duty cycle 0.3



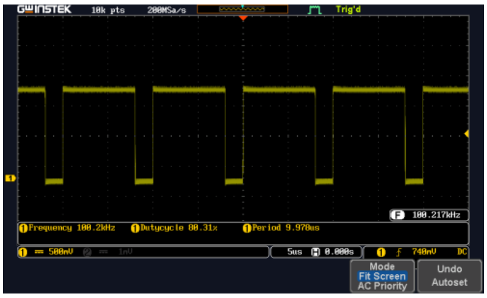
(d) Duty cycle 0.4



(e) Duty cycle 0.5

(f) Duty cycle 0.6

(g) Duty cycle 0.7



(h) Duty cycle 0.8

Figure 9: PWM signal generated using duty cycles of 0.1 to 0.8

4. Conclusion

In conclusion, this project paper has presented a comparative analysis of battery charger systems using digital control and PI controllers. A DC-DC boost converter circuit has been designed for a battery charging system by following specific battery requirement. A digital controller for the battery charger has been successfully designed by using Quartus II software. The PI controller has been successfully simulated with the boost converter circuit using MATLAB/Simulink software. The data from the simulation of the PI controller have been recorded and compared with the simulated open-loop system for further analysis. Overall, the system has better performance and in agreement with the theory.

Acknowledgement

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

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