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ARTICLE

Development of a Buck Converter for Efficient Energy Storage Integration Using Constant Voltage (CV) Methods

Ricky Alfian Dita[1], Sudirman Palaloi[2,*], Rezi Delfianti[1], Catur Harsito[3], Muhammad Nevandra Fithra Pangestu[1], Deo Ferdi Ramadhan[1], Tovva Firdansyah Amijaya[1], Farhan Mudzaffar[1] and Dimas Raka Buana Putra[1]

[1]Department of Engineering, Faculty of Advanced Technology and Multidiscipline, Airlangga University, Surabaya, 60115, Indonesia
[2]Intelligent Electricity Research Group, Research Center for Energy Conversion and Conservation, National Research and Innovation Agency, South Tangerang, 15314, Indonesia
[3]Department of Mechanical Computer Industrial Management Engineering, Kangwon National University, Samcheok, 25913, Republic of Korea

*Corresponding Author: Sudirman Palaloi. Email: sudi011@brin.go.id

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ABSTRACT: Efficient battery charging requires a power conversion system capable of providing precise voltage regulation tailored to the battery's needs. This study develops a buck converter with a 36 V input for charging a 14 V battery using the Constant Voltage (CV) method. The system is designed to ensure safe and efficient charging while protecting the battery from overcharging and extending its lifespan. In the proposed design, the converter maintains a constant output voltage while the charging current decreases as the battery approaches full capacity. Pulse Width Modulation (PWM) is used as a control strategy to modify the duty cycle of the converter. This keeps the voltage output stable whenever the load changes. The design process involves simulation and experimental validation to evaluate the system's performance and efficiency. The test results show the significant impact of Proportional-Integral-Derivative (PID) control on the stability of the output voltage to meet the requirements for 14 V battery charging and the efficiency of the battery charging process. The output voltage becomes more stable, with reduced oscillation and minimal steady-state error. The State of Charge (SOC) increases more stably, controllably, and efficiently thanks to the PID controller's ability to adjust the duty cycle in real time based on system feedback. This dynamic adjustment ensures that the output current and voltage remain within the optimal range, which directly improves the battery charging process. In addition, PID control significantly improves the dynamic response of the system, reducing overshoot and settling time while maintaining precise voltage regulation. This speeds up the battery charging process and contributes to better energy efficiency, reduced power loss, and extended battery life. This research provides a reliable and cost-effective solution for applications in electric vehicles, renewable energy systems, and other battery-powered devices.

KEYWORDS: Battery charging; buck converter; constant voltage; energy storage system

1 Introduction

Technological advances have increased the demand for efficient and reliable battery charging systems [1]. This is driven by the rapid growth of devices that rely on battery power, such as electric vehicles, renewable energy storage systems, and portable electronic devices [2]. Charging efficiency becomes a key factor in supporting the performance and durability of these devices, thus requiring solutions capable of precise voltage regulation tailored to battery needs [3].

One of the widely used power conversion topologies in battery charging applications is the buck converter [4,5]. This converter offers advantages in terms of high efficiency and simple design, making it an ideal choice for step-down voltage applications. The buck converter's ability to convert higher input voltage into lower output voltage with optimal efficiency makes it well-suited for battery-charging needs that require stable voltage regulation [6].

The Constant Voltage (CV) charging method is an effective technique for maintaining the safety and efficiency of battery charging. In this method, the converter maintains a constant output voltage while the charging current gradually decreases as the battery approaches full capacity. This technique not only protects the battery from overcharging risks but also helps extend the battery's lifespan by avoiding excessive thermal and electrical stress.

Stable voltage regulation in a buck converter requires a reliable control strategy. A commonly-used approach is pulse width modulation (PWM)-based control, where the converter's duty cycle is adjusted to produce the desired output voltage [7]. A Proportional-Integral (PI) controller is used to improve the accuracy and stability of voltage regulation. It can respond dynamically to changes in load and keep the system's efficiency high [8,9].

This study aims to design and implement a buck converter with a 36 V input for charging a 14 V battery using the CV method. The design process includes simulation and experimental validation to evaluate the system's performance under varying load conditions. The main focus of this research is to ensure the converter can deliver stable voltage regulation, high efficiency, and battery protection from potential risks during the charging process.

The results of this research are expected to provide a reliable and cost-effective solution for various applications, including electric vehicles, renewable energy systems, and other battery-powered devices. With a comprehensive design approach, this study contributes to the development of more efficient, safe, and sustainable battery charging technology in the future.

2 The DC-DC Buck Converter Circuit

2.1 Buck Converter

The Direct Current to Direct Current (DC-DC) Buck Converter operates by using a high-frequency switch (typically a transistor) or Metal-Oxide-Semiconductor Field-Effect transistor (MOSFET) that alternates between ON and OFF states. When the switch is ON, current flows through the inductor and the load, storing energy in the inductor. When the switch is OFF, the inductor releases this stored energy to the load while maintaining a continuous flow of current due to its inductive properties [10].

The key to controlling the output voltage in a buck converter is the duty cycle, which refers to the ratio of the time the switch is ON to the total switching period [11]. By adjusting the duty cycle, the output voltage can be controlled. The Pulse Width Modulation (PWM) signal regulates the timing of the ON-OFF cycles, allowing for fine control of the voltage level. In a typical buck converter, a lower duty cycle results in a lower output voltage, and a higher duty cycle leads to a higher output voltage, with the output voltage being a fraction of the input voltage. This makes buck converters ideal for applications with a lower, stable voltage from a higher input voltage source.

The buck converter is highly efficient due to its ability to directly switch energy between the inductor and the load with minimal energy losses compared to other methods of voltage regulation. The efficiency also depends on component quality, inductor design, and PWM signal control. In summary, the PWM signal and duty cycle control the operation of the switch in the buck converter, determining how long it stays ON or OFF, which ultimately regulates the output voltage. Fig. 1 depicts the circuit diagram of a buck converter [12].

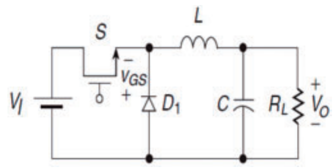

Figure 1: Buck converter circuit

Fig. 1 illustrates the switch in a Buck Converter, which operates continuously. The speed of the switch (in practical implementation) depends on the duty cycle and the frequency employed. The switching system utilizes a MOSFET as the switch, operating in two distinct modes: ON mode and OFF mode [13].

2.2 ON Mode of the Switch

In the ON position, the MOSFET is closed (conducting), and the diode is in the OFF state. During this mode, current flows from the source to the inductor (inductor charging phase), where it is filtered by the capacitor before passing to the load, and subsequently returns to the source [14].

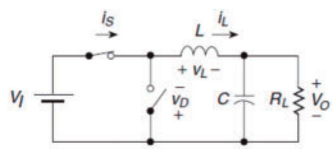

Figure 2: Circuit configuration during switch closed

From Fig. 2, the voltage across the inductor can be expressed as [13]:

$$V_L = V_s - V(t) \tag{1}$$

The voltage ripple equation is given by:

$$V_L = V_s - V \tag{2}$$

The current flowing through the inductor during the ON state is expressed as [15]:

$$VL(t) = L\left(\frac{diL(t)}{dt}\right) \tag{3}$$

$$\left(\frac{diL(t)}{dt}\right) = \left(\frac{VL(t)}{L}\right) \simeq \left(Vs - \frac{V}{L}\right) \tag{4}$$

2.3 OFF Mode of the Switch

In the OFF position, the MOSFET is open (non-conducting), and the diode becomes forward-biased (conducting). During this mode, the current flows through the inductor (L), capacitor (C), load, and diode [16]. The inductor current decreases until the transistor is turned on again in the next cycle. The energy stored in the inductor during the ON mode is transferred to the load in this phase.

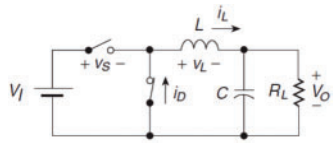

Figure 3: Circuit when the switch is open

From Fig. 3 above, the voltage at the inductor can be formulated as follows [17]:

$$VL(t) = -V \tag{5}$$

Ripple voltage formula:

$$VL \approx Vs - V \tag{6}$$

The current flowing through the indicator at the time of the OFF condition is expressed in the formula:

$$VL(t) = L\frac{diL(t)}{dt} \tag{7}$$

$$\frac{diL(t)}{dt} \simeq \frac{V}{L} \tag{8}$$

2.4 Buck Converter Calculation

The calculation of a buck converter involves determining several key parameters to ensure optimal performance. The main variables to consider include input voltage, output voltage, output current, and switching frequency. From these variables, the duty cycle, input power, output power, and efficiency can be determined to achieve a stable output voltage while minimizing current and voltage ripple [18]. These parameters can be calculated using the following equations:

Duty Cycle

$$D = \frac{V_o}{V_i} \times 100\% \tag{9}$$

Input Power

$$P_i = V_i \times I_i \tag{10}$$

Output Power

$$P_o = V_o \times I_o \tag{11}$$

Efficiency

$$n = \frac{V_o \times I_o}{V_i \times I_i} \times 100\% \tag{12}$$

2.5 PI Control

Proportional-Integral (PI) control is a commonly used feedback control method in buck converters to maintain a stable output voltage [19]. The PI controller operates by processing the error signal, which is the difference between the actual output voltage (Vout) and the reference voltage (Vref), to generate a control signal that adjusts the PWM duty cycle of the MOSFET. Fig. 4 illustrates the cascade PI control system for the buck converter.

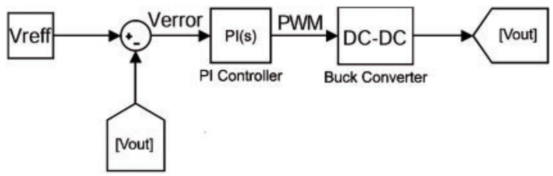

Figure 4: Cascaded closed-loop control for buck converter

3 Method

This section outlines the methodological approach undertaken to design, simulate, and implement a DC-DC buck converter for charging a 14 V battery from a 36 V input using the Constant Voltage (CV) method. The flowchart and block diagram below provide a detailed overview of the design and implementation steps.

3.1 Flowchart

The design and implementation procedure for a 36 V buck converter that uses the constant voltage (CV) approach to charge a 14 V battery is depicted in the flowchart in Fig. 5. The process begins with defining the system requirements, including input and output voltage specifications, target efficiency, and safety measures for battery protection. Next, the design parameters, such as the inductor, capacitor, and switching frequency, are calculated to ensure optimal performance. A control strategy based on Pulse Width Modulation (PWM) is then developed to regulate the duty cycle of the converter. This is followed by the design and tuning of a Proportional-Integral (PI) controller to maintain stable voltage output under varying load conditions. The system design is simulated in software to verify its performance, including voltage regulation and efficiency metrics. Finally, the buck converter is implemented in hardware, and experimental testing is conducted to validate the design against the simulation results, ensuring it meets the requirements for safe and efficient 14 V battery charging.

3.2 Parameter Buck Converter

A buck converter has the primary characteristic of reducing a higher input voltage to a lower and controlled output voltage. Consequently, the output voltage can be adjusted according to application requirements, such as battery charging. The operational parameters will be presented in Table 1 to provide a clearer overview of its specifications.

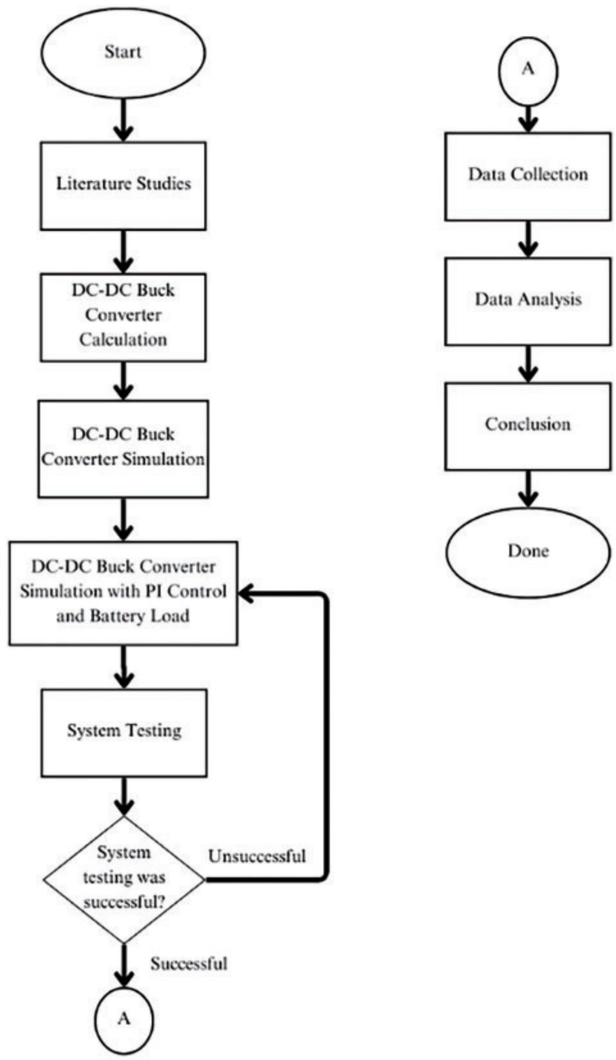

Figure 5: Flowchart of buck converter using constant voltage methods

Table 1: Parameter of buck converter

Parameter	Value
Input voltage (Vin)	36 V
Output voltage (Vout)	14 V
Inductor	30 μH
Capacitor	2000 μH
Resistor	10 Ω
Duty cycle	38.88%
Switching frequency	40 kHz

3.3 Block Diagram

The following Fig. 6 presents a block diagram of a DC-DC buck converter system for charging batteries that relies on MOSFETs as the main switching elements.

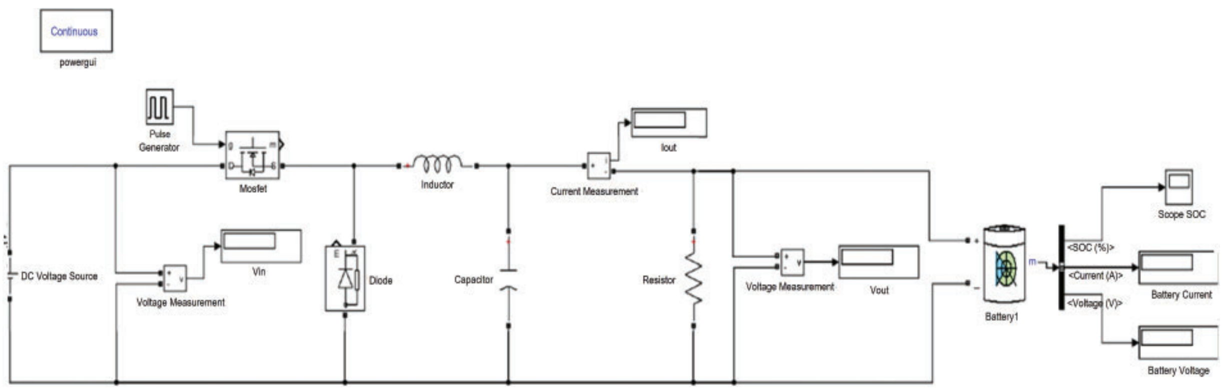

Figure 6: DC-DC buck converter system for battery charging

Fig. 6 presents the block diagram of the DC-DC buck converter system for charging a 14 V battery from a 36 V input, focusing on the core hardware configuration. The system relies on a MOSFET as the main switching element, driven by a pulse generator to control the duty cycle of the switch [20]. Key components include an inductor and capacitor for filtering, a diode for directing current flow during the switch OFF state, and current measurement points for monitoring input and output currents. The output is connected to the battery, with its voltage, current, and State of Charge (SOC) displayed and analyzed [21]. This setup represents a simplified design aimed at demonstrating the fundamental operation of the buck converter while ensuring stable and efficient charging of the battery.

However, it should be noted that this configuration is an idealized representation of the buck converter system. In real-world applications, various additional considerations, such as thermal management, efficiency optimization, and protection mechanisms for over-voltage and over-current conditions, need to be incorporated into the design to ensure safe and reliable operation over prolonged periods. Moreover, the pulse width modulation (PWM) control method, while effective in most scenarios, might face limitations in handling dynamic load variations and temperature fluctuations, which could affect the performance and lifespan of both the converter and the battery. Further refinement and testing are essential to adapt this basic configuration for practical deployment in diverse environments and applications.

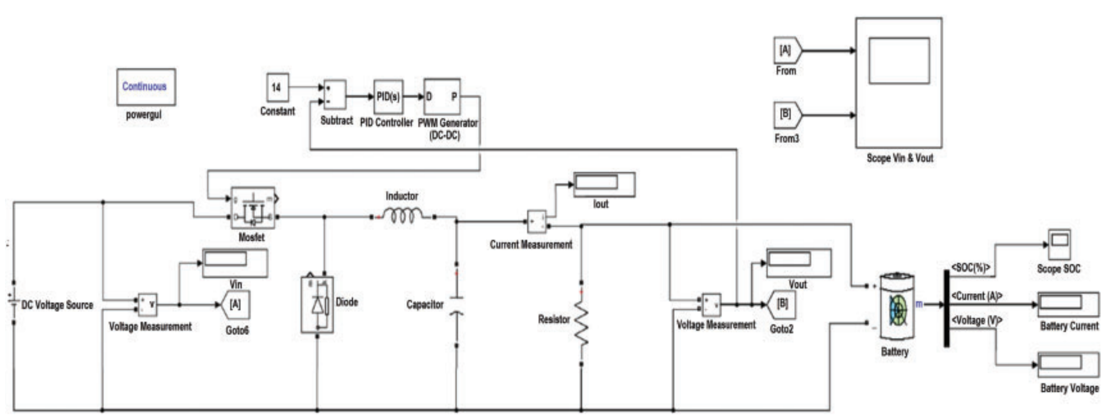

Figure 7: DC-DC buck converter system for battery charging using PI controller

Fig. 7 illustrates the block diagram of the proposed DC-DC buck converter system for charging a 14 V battery from a 36 V DC input using the Constant Voltage (CV) method. The system is designed with key components, including a MOSFET as the switching element, an inductor (L) and capacitor (C) for energy storage and filtering, and a diode to direct current during the OFF state of the switch. A Proportional-Integral (PI) controller is employed to regulate the duty cycle of the Pulse Width Modulation (PWM) signal, ensuring stable output voltage despite load variations [22].

The primary objective of using the CV method is to maintain a constant output voltage to the battery during the charging process. The inclusion of a PI controller adds a crucial layer of control to the system by dynamically adjusting the PWM signal based on real-time feedback from the system's voltage. The PI controller plays a vital role in minimizing the steady-state error, which is the difference between the desired output voltage and the actual output voltage. This is especially important in battery-charging applications where the battery voltage needs to remain within a specific range for efficient and safe charging.

In addition to improving voltage accuracy, the PI controller enhances the system's dynamic response to changes in load. For instance, if the battery draws more current due to a change in its internal resistance or charging conditions, the PI controller adjusts the duty cycle of the PWM signal to maintain the constant voltage [23]. This results in the reduction of voltage ripple, which can be detrimental to the battery health over time, and helps compensate for any external disturbances or fluctuations in input voltage. As a result, the DC-DC buck converter system becomes more reliable, efficient, and adaptable to varying conditions during battery charging [24].

4 Results and Discussion

4.1 Simulation Results of the Buck Converter under State of Charge without PID

Based on the simulation results of the buck converter, in Fig. 8, under the battery's State of Charge (SOC) condition without Proportional-Integral-Derivative (PID) control, it is observed that the SOC increases linearly from 50% to approximately 50.035% over a simulation time of 0.5 s. The graph shows a stable and nearly straight increase, indicating that the buck converter can steadily increase the battery's SOC. However, the SOC increase rate is very slow because the buck converter operates in open-loop mode with a fixed duty cycle. Without dynamic control, the output current and voltage are not optimized for the battery charging requirements, causing the charging process to be inefficient.

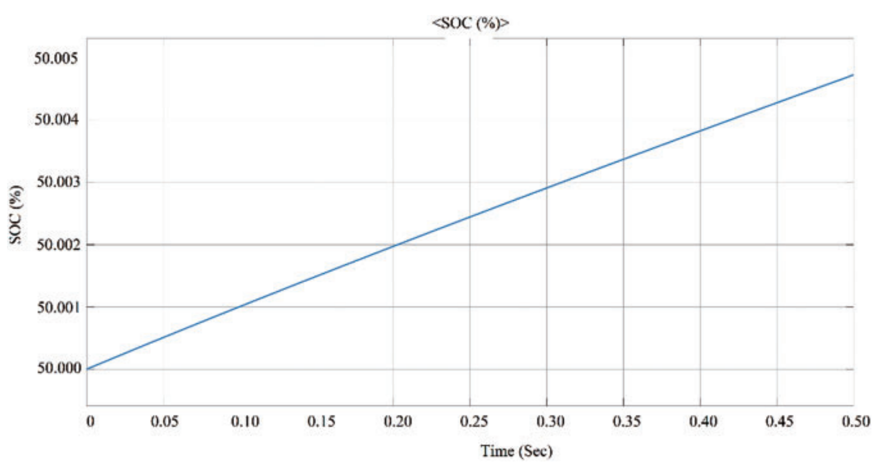

Figure 8: Simulation results of the buck converter under State of Charge without PID

This slow SOC growth highlights the limitations of an open-loop control system, where the converter cannot adjust to varying battery conditions, such as changes in internal resistance, temperature, or SOC levels. In such systems, the fixed duty cycle results in a static output voltage and current, which may not align with the optimal charging profile of the battery. This leads to inefficient energy transfer, prolonged charging times, and potential stress on the battery over extended periods. Moreover, the absence of feedback mechanisms means the system cannot compensate for disturbances, such as input voltage fluctuations or load variations, which could further degrade performance.

4.2 Simulation Results of the Buck Converter under State of Charge with PID

The performance of the buck converter can be significantly improved by implementing Proportional-Integral-Derivative (PID) control. PID control dynamically adjusts the duty cycle in real time based on continuous feedback from the battery's voltage and current conditions. This ensures that the output current and voltage are always optimized for the specific charging stage of the battery—whether it's bulk charging, absorption, or float stage. The proportional component of the PID controller responds to the current error, the integral component eliminates steady-state errors, and the derivative component anticipates future trends based on the rate of change, providing a more stable and responsive control system.

With PID control, the charging process will be faster and more efficient as it can dynamically respond to changes in battery conditions, such as variations in SOC, temperature, or load demands. This results in a more consistent charging current, reduced ripple, and improved battery health over time. Although the simulation results without PID control show a stable SOC increase, the absence of dynamic adjustment mechanisms causes a significantly longer charging time and potential inefficiencies. Therefore, implementing PID control is highly recommended to improve efficiency, accelerate the battery SOC increase, and enhance the overall reliability of the charging system.

Based on the experimental data in Table 2 of the buck converter with PID control, it is observed that the output voltage (V_{out}) approaches the reference voltage (V_{ref}) of 14 V as the P, I, and D control parameters are adjusted. In the initial trials (rows 1–3), the control parameter values were still low, resulting in V_{out} not reaching the V_{ref} value, with a significant error ranging between 0.25 and 0.27 V. This indicates that the system was not yet capable of providing an accurate response to maintain output voltage stability. However, as the values of the Proportional (P) and Integral (I) controls increased in subsequent trials, the error between V_{ref} and V_{out} gradually decreased. For instance, in row 10, with P = 2.5 and I = 5, the error reduced to 0.06 V.

At the optimal condition in row 16, with P = 30 and I = 66, the output voltage V_{out} reached 14 V, matching the reference voltage V_{ref}, resulting in an error of 0 V. This demonstrates that proper tuning of the PID control parameters can achieve a stable output voltage that matches the reference value. The P control improves the system's response speed, while the I control eliminates the steady-state error. In this experiment, the D (Differential) control was set to zero, and therefore, it did not have a significant effect on oscillation damping. Thus, the PID control system proved to be effective in regulating the buck converter's performance, achieving a stable output voltage with near-zero error.

Table 2: Data of buck converter with PID control

V_{in} (V)	Control			V_{ref} (V)	V_{out} (V)	Error
	P	I	D			
36	1.0	1.0	0	14	13.75	0.25
36	1.0	0.1	0.1	14	13.62	0.38

(Continued)

Table 2 (continued)

V_{in} (V)	Control			V_{ref} (V)	V_{out} (V)	Error
	P	I	D			
36	1.0	0.8	0	14	13.73	0.27
36	1.2	1.5	0	14	13.82	0.18
36	1.2	2.0	0	14	13.85	0.15
36	1.5	2.5	0	14	13.88	0.12
36	1.8	3.2	0	14	13.91	0.09
36	2.0	3.8	0	14	13.92	0.08
36	2.4	4.5	0	14	13.93	0.07
36	2.5	5.0	0	14	13.94	0.06
36	3.8	5.7	0	14	13.95	0.05
36	4.2	7.5	0	14	13.96	0.04
36	5.5	9.5	0	14	13.97	0.03
36	9.0	14.5	0	14	13.98	0.02
36	13.0	31.0	0	14	13.99	0.01
36	30.0	66.0	0	14	14.00	0.00

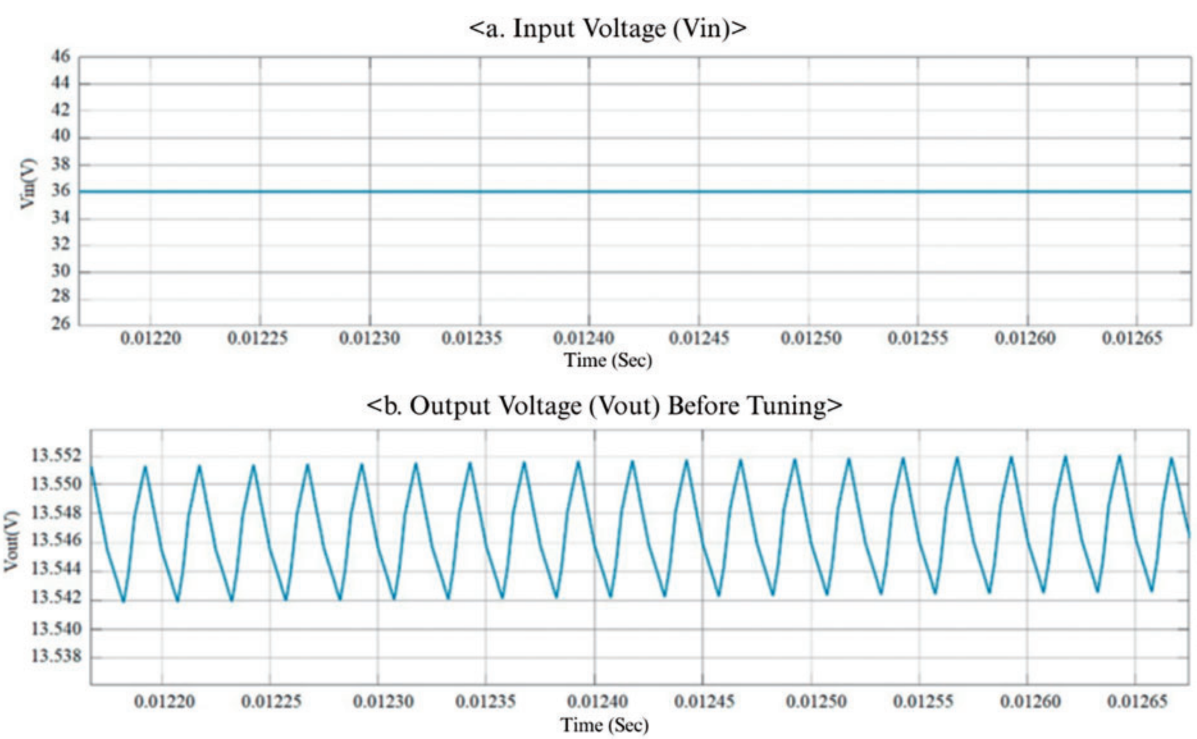

Figure 9: Buck converter output simulation graph before tuning **(a)** Input voltage (Vin) **(b)** Output voltage (Vout) Before tuning

Fig. 9 provides a comprehensive overview of the buck converter's electrical behavior by presenting both the input and output voltage characteristics. The stability of the input voltage and the initial performance of the output voltage before PID tuning are analyzed to establish a baseline for evaluating the system's overall regulation capabilities. These observations form the foundation for understanding how the converter responds under standard conditions and highlight areas where control improvements are necessary.

a. Input Voltage (Vin)

The first subplot in Fig. 9a shows the input voltage (Vin) to the buck converter. As seen in the graph, the input voltage remains constant at approximately 36 V over time. This stability is crucial for the proper operation of the buck converter, as a steady input ensures that any variations observed at the output are not caused by fluctuations in the source voltage. In a well-designed buck converter system, the input voltage should be reliably regulated or provided by a stable source, which allows the controller to focus solely on adjusting the output voltage without compensating for input disturbances. The flat, unwavering line on the Vin graph indicates that the input power supply is operating correctly and provides a strong foundation for evaluating the performance of the output regulation system.

b. Output Voltage (Vout) before Tuning

The second subplot in Fig. 9b output voltage (Vout) before tuning, illustrates the output voltage (Vout) of the buck converter before PID tuning. The graph clearly shows significant oscillations around the desired setpoint, highlighting that the system is not yet stable. These oscillations occur due to improper tuning of the Proportional (P), Integral (I), and Derivative (D) gains within the PID controller. When the proportional gain is set too high, the system reacts too aggressively to errors, causing excessive overshoot and oscillations. Similarly, if the integral gain is not properly adjusted, it can slow the system's response to steady-state errors, resulting in prolonged deviations from the target voltage. Moreover, poorly configured derivative gain may either fail to dampen oscillations or may even amplify high-frequency noise, exacerbating instability.

The presence of a steady-state error, where the output voltage fails to consistently reach and maintain the setpoint, highlights the inefficiency of the control loop. This can negatively affect the battery charging process, as unstable voltage levels may reduce charging efficiency, generate excess heat, and potentially shorten the battery's lifespan. Furthermore, these oscillations can cause stress on the electronic components within the converter, increasing the risk of wear and failure over time.

To address these issues, PID tuning is essential. The tuning process involves systematically adjusting the P, I, and D parameters to achieve an optimal balance between response speed, stability, and accuracy. Proper tuning will minimize oscillations, reduce overshoot, and eliminate steady-state error, resulting in a smooth, stable output voltage. This, in turn, ensures efficient energy transfer, enhances battery health, and improves the overall performance of the buck converter system.

Fig. 10 presents a detailed analysis of the buck converter's input and output voltage behaviors following the PID tuning process. By examining both the stability of the input voltage and the performance of the output voltage after tuning, the overall effectiveness of the control strategy can be assessed. These insights provide a clear understanding of how optimal tuning impacts the converter's ability to maintain a steady and reliable output, forming the basis for evaluating system improvements in dynamic operating conditions.

The graph shown in Fig. 10a illustrates the input voltage (Vin) of the buck converter over a period of 0.5 s. As observed, the input voltage remains consistently steady at approximately 36 V without any noticeable fluctuations or disturbances. This indicates that the power source feeding the buck converter is highly stable and not influenced by external perturbations during the test period. The constancy of the input voltage is critical for evaluating the effectiveness of the PID tuning, as it ensures that any improvements observed in the output voltage are due solely to the control strategy applied rather than variations in the input supply.

Therefore, this stable Vin serves as a reliable reference point for assessing the performance enhancements introduced by the PID controller.

In Fig. 10b, output voltage (Vout) after tuning, the output voltage of the buck converter shows significant improvement compared to the pre-tuning condition. The voltage output becomes much more stable and consistently approaches the desired setpoint value. The oscillations and fluctuations that were previously present have been effectively dampened, resulting in a constant and reliable output. This improvement highlights the critical role of optimal PID tuning in enhancing the buck converter's performance. By precisely adjusting the Proportional (P), Integral (I), and Derivative (D) parameters, the system can dynamically respond to load variations, minimize steady-state errors, and eliminate unwanted overshoot or undershoot. Interestingly, the input voltage remains constant in both the pre- and post-tuning conditions, indicating that the enhanced stability of the output voltage is solely due to the optimized PID control rather than any changes in the power source. This demonstrates that PID tuning not only improves voltage regulation but also enhances system efficiency, making the converter more reliable and effective for applications such as battery charging.

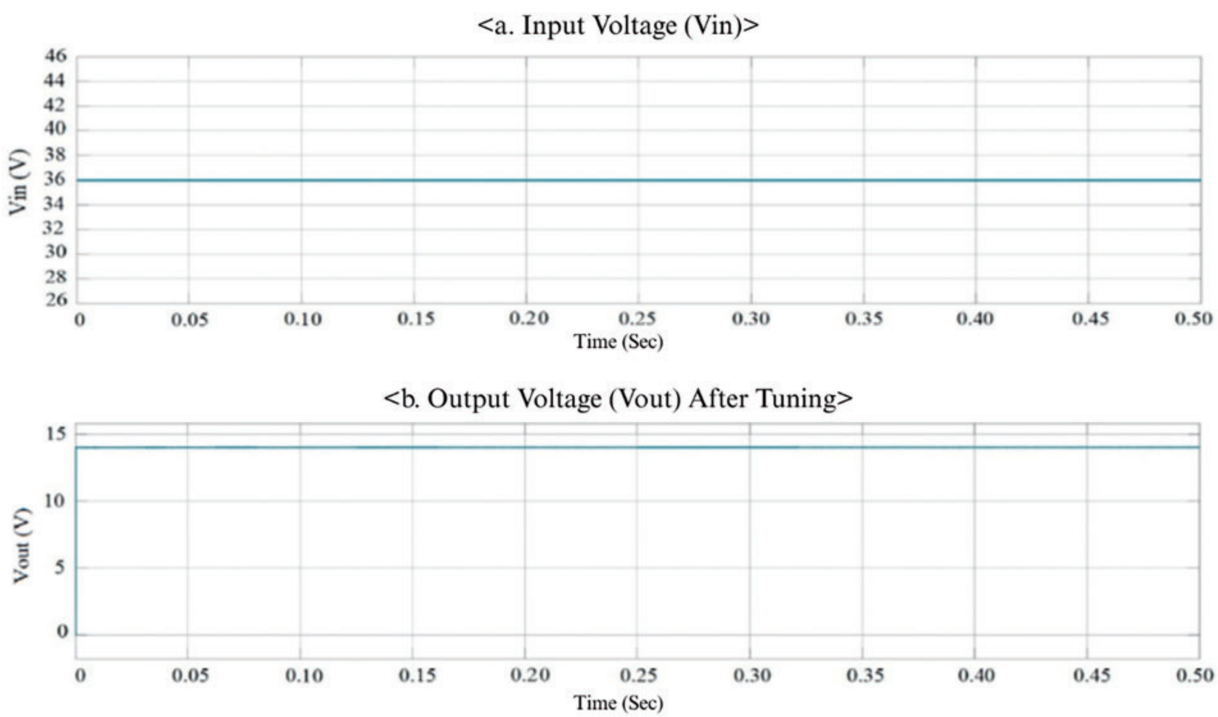

Figure 10: Buck converter output simulation graph after tuning **(a)** Input voltage (Vin) **(b)** Output voltage (Vout) After tuning

In Fig. 11, the simulation results of the buck converter using PID control demonstrate a significant improvement in the battery's SOC behavior compared to the system without PID control. The SOC graph starts at around 50% and gradually increases to approximately 50.045% by the end of the simulation. Unlike the linear yet slow increase observed in the open-loop system (without PID), the SOC curve here exhibits a smoother and more stable trend, free from abrupt fluctuations or irregularities. This indicates that the PID controller successfully regulates the output voltage and current, creating an optimal environment for the battery charging process.

The PID control mechanism plays a crucial role in enhancing the system's performance. It continuously adjusts the duty cycle of the Pulse Width Modulation (PWM) signal based on real-time feedback from the system, effectively minimizing steady-state errors and improving the dynamic response. The Proportional (P) component addresses immediate deviations from the setpoint, the Integral (I) component eliminates long-term errors by accounting for accumulated discrepancies, and the Derivative (D) component anticipates future errors based on the current rate of change. This combination ensures faster and more accurate system responses, leading to a stable charging process with reduced overshoot and minimal ripple in the output voltage.

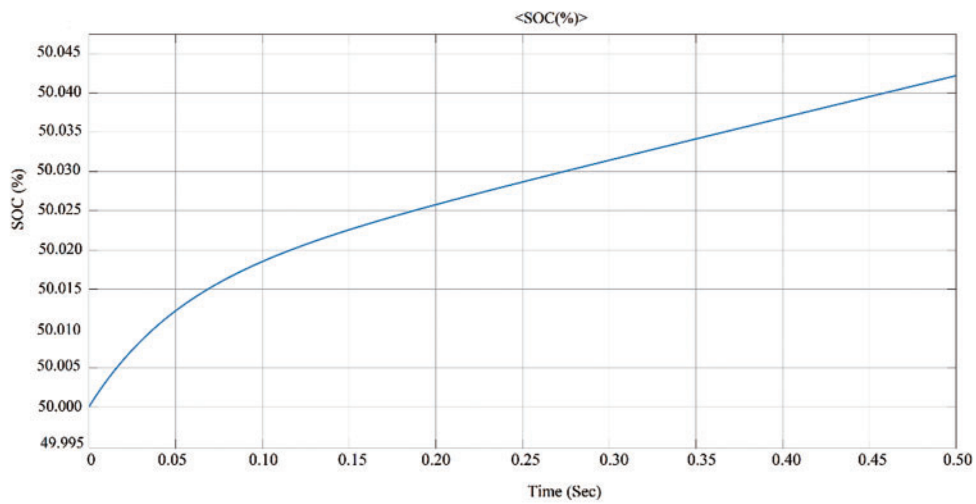

Figure 11: Buck converter output simulation graph for SOC with PID

Furthermore, the implementation of PID control enhances the efficiency of the buck converter. By maintaining the output voltage within the optimal range for battery charging, the system reduces energy losses and avoids stressing the battery with sudden voltage spikes. This not only accelerates the SOC increase but also prolongs the battery's lifespan due to more controlled charging conditions. The steady SOC growth curve reflects the converter's ability to dynamically adapt to changing battery conditions, ensuring consistent performance regardless of fluctuations in load or input conditions.

In conclusion, the detailed simulation results in Fig. 11 confirm that the application of PID control in the buck converter significantly improves the efficiency, stability, and reliability of the battery-charging process. The SOC increases more effectively, the system responds swiftly to disturbances, and the overall performance of the buck converter reaches an optimized state.

5 Conclusion

In this study, the implementation of PID control in a DC-DC buck converter system for battery charging has been thoroughly analyzed through simulation. The results demonstrate the significant impact of PID control on both the stability of the output voltage and the efficiency of the battery charging process. Without PID control, the buck converter operates in an open-loop mode with a fixed duty cycle, resulting in output voltage fluctuations, slower system response, and inefficient battery charging. The State of Charge of the battery increased linearly but very slowly, indicating suboptimal performance due to the lack of dynamic control over the output parameters.

Conversely, with the implementation of PID control, the system exhibited remarkable improvements. The output voltage became more stable, with reduced oscillations and minimal steady-state errors. The SOC increased more stably, controlled, and efficiently, thanks to the PID controller's ability to adjust the duty cycle in real-time based on feedback from the system. This dynamic adjustment ensured that the output current and voltage remained within optimal ranges, directly enhancing the battery charging process.

Moreover, PID control significantly improved the system's dynamic response, reducing overshoot and settling time while maintaining precise voltage regulation. This not only accelerates the battery charging process but also contributes to better energy efficiency, reduced power losses, and extended battery lifespan. The proportional, integral, and derivative components work synergistically to optimize system performance under varying load conditions, ensuring that the converter responds effectively to any disturbances or changes.

In conclusion, the simulation results confirm that PID control is essential for improving the performance of buck converters in battery-charging applications. It enhances voltage stability, optimizes the charging process, and ensures higher system efficiency, making it a crucial component for modern power management systems. Future work can explore advanced control strategies, such as adaptive PID or fuzzy logic controllers, to further improve performance under more complex operating conditions.

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Nomenclature

Buck Converter	DC-DC power converter that steps down voltage from input to output
C	Capacitor
Constant Voltage (CV)	Battery charging method maintaining fixed voltage while current decreases
D	Derivative gain
DC-DC	Direct current to direct current
di/dt	Rate of change of current
Duty Cycle	Ratio of switch ON time to total switching period
I	Integral gain

Il	Inductor current
L	Inductance/Inductor
$MOSFET$	Metal-Oxide-Semiconductor Field-Effect Transistor (switching element)
P	Proportional gain
PI	Proportional-Integral
PID	Proportional-Integral-Derivative controller
PWM	Pulse Width Modulation
$State\ of\ Charge\ (SOC)$	Battery's current charge level as percentage of full capacity
$V(t)$	Output voltage
Vin	Input voltage
VL	Voltage across inductor
$Vout$	Actual output voltage
$Vref$	Reference/target voltage

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