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Design and Implementation of a Digital PID Controller for DC–DC Buck Converter with MATLAB

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ABSTRACT

This study focuses on the design and implementation of a digital Proportional-Integral-Derivative (PID) controller for a DC-DC buck converter using MATLAB. The main issue addressed is the need for better voltage regulation in power electronics applications, which is critical to maintaining system stability and performance. The objective of this study is to develop a robust control strategy that minimizes output overvoltage and improves accuracy under varying load conditions. The methodology used involves the development of a discrete-time PID controller, which is simulated in MATLAB to analyze its performance. The results in MATLAB show that the digital PID controller successfully limits overvoltage and maintains output voltage stability, even with significant load variations. Further experimental validation confirms the simulation results, demonstrating the controller's ability to adapt to real-world conditions. The successful implementation and validation of the controller using MATLAB underscores its potential to improve the efficiency and reliability of power conversion systems.

1. Introduction

The advancement of power electronics has led to the widespread adoption of DC-DC converters in various applications, ranging from consumer electronics to renewable energy y systems. Among these converters, the buck converter is particularly valued for its efficiency and simplicity in stepping down voltage levels. However, the performance of buck converters can be significantly influenced by various dynamic factors, necessitating the implementation of robust control strategies to ensure stability and responsiveness. One such approach is the Proportional-Integral-Derivative (PID) control, which is renowned for its effectiveness in managing system dynamics and improving transient response [48]. The design and tuning of a PID controller for a buck converter using MATLAB can facilitate real-time simulation and analysis, allowing engineers to optimize control parameters for desired performance outcomes [27][1]. This process not only enhances the converter's efficiency but also minimizes overshoot and settling time, leading to a more reliable power supply for various applications. In addition, incorporating advanced techniques such as feedforward control and adaptive algorithms can further enhance the performance of buck converters by dynamically adjusting to changes in load conditions and input voltage variations [26].

These enhancements contribute to a more robust system that can maintain stability and performance under varying operational scenarios, ultimately resulting in increased longevity and reliability of electronic devices. Engineers can leverage these advancements to design systems that not only meet current demands but also adapt to future challenges, ensuring sustained performance in an ever-evolving technological landscape. This adaptability is crucial in industries such as renewable energy, electric vehicles, and consumer electronics, where efficiency and reliability are paramount for success [10].

This research focuses on the design and implementation of a digital PID controller specifically tailored for a DC-DC buck converter, utilizing MATLAB as the primary simulation and development platform. The integration of digital control techniques allows for enhanced precision and adaptability in real-time applications, addressing the challenges posed by non-linearities and disturbances in the system. Furthermore, the inclusion of a bump test methodology provides a comprehensive assessment of the controller's performance, facilitating the identification of optimal tuning parameters and ensuring the reliability of the converter under varying operational conditions. This study aims to contribute to the existing body of knowledge by exploring the intricacies of digital PID control in buck converters and demonstrating its efficacy through simulation-based experiments in MATLAB.

As power electronics continue to evolve, examining these advanced methodologies will be crucial for optimizing the efficiency and reliability of DC-DC converters in diverse applications. Research into these advanced control strategies not only enhances the performance of buck converters but also paves the way for innovative designs that can meet the increasing demands of modern electronic systems.

2. Methods

In order to emphasize the nonlinear dynamics of the system, the controller design for a DC-DC buck converter starts with mathematical modeling that analyzes voltage and current characteristics throughout switching states [25]. Based on the system's open-loop response, the parameters of the PID controller design proportional gain (Kp), integral time (Ti), and derivative time (Td) are first determined using MATLAB's PID Tuner tool [6].

For performance refinement, the bump test auto-tuning technique is employed to determine final gain and frequency parameters, enhancing controller resilience under load [15]. MATLAB/Simulink simulations validate the tuning by evaluating stability, settling time, and overshoot [10], ensuring a reliable controller for various converter designs [22].

2.1. Modelling of DC-DC Buck Converter

A buck converter is a DC-DC converter designed to efficiently step down a higher input voltage (Vin) to a lower output voltage (Vo) using pulse-width modulation (PWM) [26]. The main components include a switch (transistor) to control the connection and disconnection of the input voltage, a diode to provide a path for the inductor current when the switch is off, an inductor (L) to store energy and smooth current flow, a capacitor (C) to reduce voltage ripple and stabilize the output voltage, and a resistor (R) representing the load. The working principle involves the switch turning ON [26]. allowing the inductor to store energy from the input voltage, and turning OFF, during which the inductor releases stored energy to the load, ensuring a continuous current flow [6].

$$\frac{Y(s)}{Yref(s)} = \frac{\frac{Vi}{LC}Gc(s)}{s^2 + \frac{1}{RC}s + \frac{1}{LC} + \frac{Vi}{LC}Gc(s)} \tag{1}$$

$$Gc(s) = \frac{Kd\,s^2 + Kp\,s + Ki}{s} \tag{2}$$

Then, substitute equation (2) to equation (1).

$$\frac{Y(s)}{Yref(s)} = \frac{\frac{Vi}{LC}(\frac{Kd\,s^2 + Kp\,s + Ki}{s})}{s^2 + \frac{1}{RC}s + \frac{1}{LC} + \frac{Vi}{LC}(\frac{Kd\,s^2 + Kp\,s + Ki}{s})}$$

$$\frac{Y(s)}{Yref(s)} = \frac{\frac{Vi}{LC}(Kd\,s^2 + Kp\,s + Ki)}{s^3 + \frac{1}{RC}s^2 + \frac{1}{LC}s + \frac{Vi}{LC}(Kd\,s^2 + Kp\,s + Ki)}$$

$$\frac{Y(s)}{Yref(s)} = \frac{\frac{Vi}{LC}Kd\,s^2 + \frac{Vi}{LC}Kp\,s + \frac{Vi}{LC}Ki}{s^3 + (\frac{1}{RC} + \frac{Vi}{LC}Kd)s^2 + (\frac{1}{LC} + \frac{Vi}{LC}Kp)s + \frac{Vi}{LC}Ki} \tag{3}$$

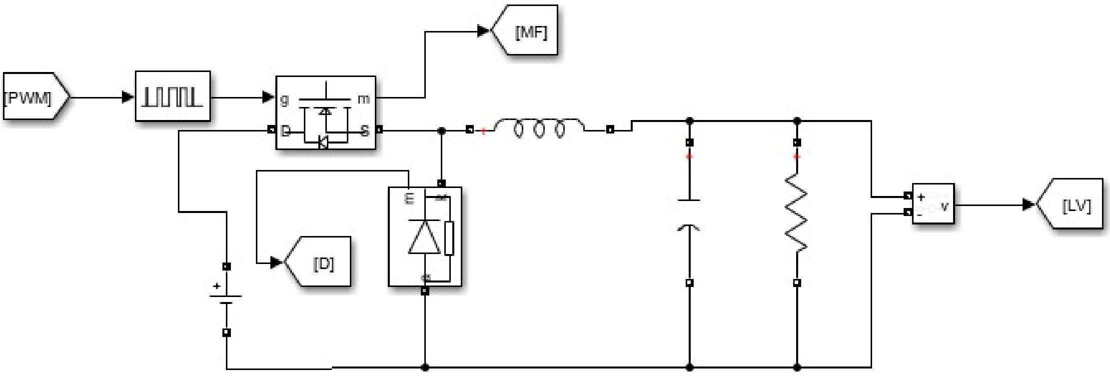


Figure 1: DC-DC Buck Converter.

The main equations with Kirchhoff's Laws used in the buck converter are

- Inductor Voltage Equation:

$$v_L = L\frac{di_L}{dt} \tag{4}$$

- Capacitor Current Equation

$$I_C = C\frac{dVC}{dt} \tag{5}$$

When the switch is ON: The inductor stores energy, and the equation becomes:

$$V_L = V_{\text{in}} - V_{\text{O}} \tag{6}$$

When the switch is OFF, The inductor releases energy, and the equation becomes:

$$V_L = -V_{\text{O}} \tag{7}$$

In steady-state operation, the relationship between Vin and Vo is given by

$$V_{in}D = Vo \tag{8}$$

Where D is the duty cycle of the pulse-width modulation (PWM), Using Kirchhoff's voltage and current laws:

- For the inductor :

$$L\frac{diL}{dt}+Ri_L=V_{in}-V_o \tag{9}$$

- For the capacitor :

$$C\frac{dV_o}{dt}+\frac{V_o}{R}=i_L \tag{10}$$

The Laplace transform converts the equations from the time domain to the s-domain for easier analysis. In the s-domain:

- For the inductor :

$$V_L\,(s)=L_s\,I_{\mathrm{L}}\,(s)-\,Li_{\mathrm{L}}\,(0) \tag{11}$$

- For the capacitor :

$$I_C\,(s)=C_s\,V_{\mathrm{O}}\,(s)-\,Cv_{\mathrm{o}}\,(0) \tag{12}$$

Substituting these equations into the time-domain model creates a relationship between Vo(s) IL(s) and Vin(s). The transfer function G(s) is defined as :

$$G(s)=\frac{V_o(s)}{u\,(s)} \tag{13}$$

Where u(s) is the input duty cycle of the PWM signal. Solving the equations for G(s) yields the final transfer function:

$$G(s)=V_{in}\left(\frac{R}{R+R_L}\right)\left(\frac{\frac{s}{\omega_{ZERO}}+1}{\frac{s^2}{\omega_0^2}+\frac{s}{Q\omega_0}+1}\right) \tag{14}$$

2.2. Numerical Simulation

To demonstrate the validity and effectiveness of the developed controller, numerical simulations were conducted using the MATLAB Simulink environment [23][16]. The simulation utilized a step input reference voltage with predefined parameters to evaluate the controller's performance [13]. under dynamic conditions. The setup includes all calculated RLC parameters and PID gain values, integrated into the circuit model for comprehensive testing.

The results demonstrate efficient output voltage regulation, with the system tracking the reference signal with minimal delay [33]. The error signal shows initial transient behavior but gradually diminishes, confirming the controller's steady-state error minimization capability [32]. The PWM signal dynamically adjusts during transients, with duty cycle changes effectively stabilizing the output [3]. These observations validate that the controller meets desired performance criteria for fast, stable voltage regulation [26].

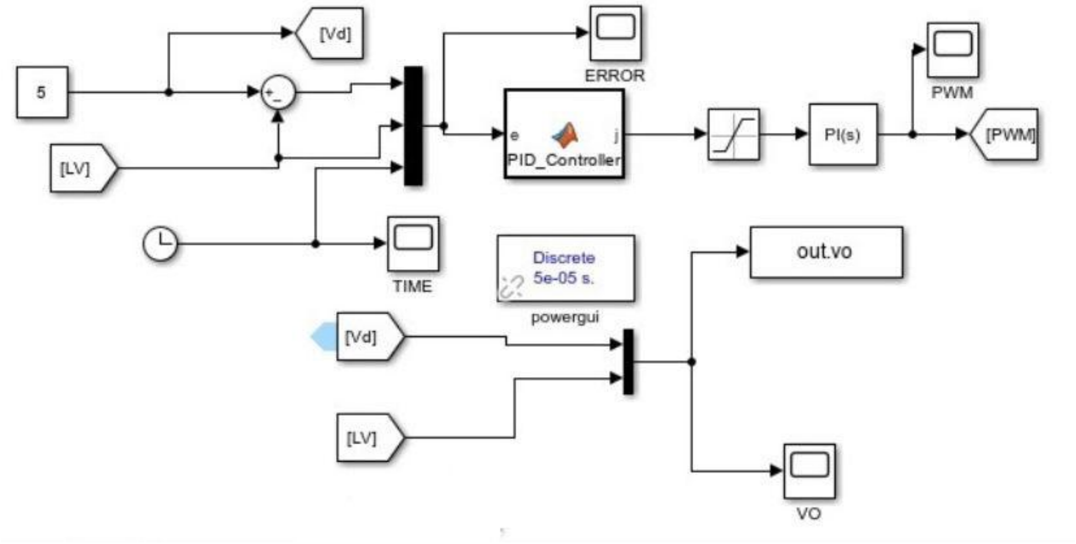
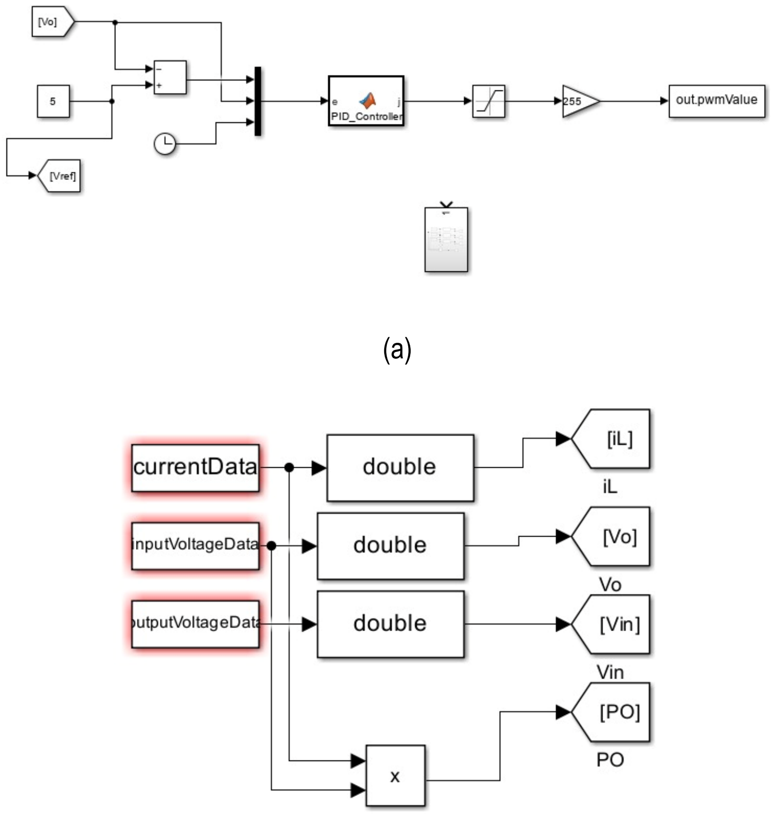


Figure 2: Simulink Model Control.



(a)

(b)

Figure 3: Simulink Model for Hardware Implementation.

2.2.1. Inductor value calculation formula

$$I_{LB} = \frac{T_s V_o}{2L}(1 - D) \tag{16}$$

$$L = \frac{T_s V_o}{2I_{LB}}(1 - D)$$

$$L = \frac{10^{-5} \times 5}{2 \times 2}(1 - \frac{1}{3})$$

$$L = \frac{10^{-5} \times 5}{4} \times \frac{2}{3}$$

$$L = \frac{5}{6} \times 10^{-5}$$

$$L = 0.833333 \times 10^{-5}$$

2.2.2. Capacitor value calculation formula

$$\Delta V_o = \frac{T_s^2}{8C} \times \frac{V_o}{L} \times (1 - D) \tag{17}$$

$$C = \frac{T_s^2}{8\Delta V_o} \times \frac{V_o}{L} \times (1 - D)$$

$$C = \frac{(10^{-5})^2}{8 \times 0.1} \times \frac{5}{\frac{5}{6} \times 10^{-5}} \times (1 - \frac{1}{3})$$

$$C = \frac{(10^{-5})^2 \times 5}{0.8 \times \frac{5}{6} \times 10^{-5}} \times \frac{2}{3}$$

$$C = \frac{10^{-5} \times 5 \times 6}{0.8 \times 5} \times \frac{2}{3}$$

$$C = \frac{10^{-5} \times 2}{0.8} \times 2$$

$$C = \frac{10^{-5} \times 4}{0.8}$$

$$C = 5 \times 10^{-5}$$

Table 1: Parameters of The Buck Converter.

Parameters	Value
Output capacitor C	5 e^{-5} uF
Inductor L	0.8333333 e^{-5} uH
Resistance load R	2.5 Ω
Frequency fs	100 KHz

2.2.3. Formula PID Controller Bump Test

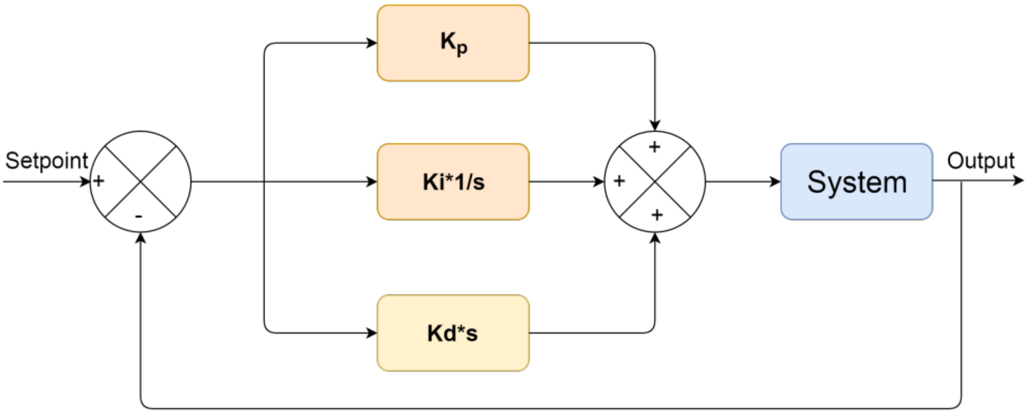


Figure 4: Parallel PID Controller form diagram.

A bump test is a method used to determine the dynamic characteristics of a system for PID controller tuning [3]. It involves introducing a step change (bump) in the input of the system, such as adjusting the setpoint or manipulating the control signal, to observe the system's response [35]. The bump test is based on system identification principles. By analyzing the system's response to the step input, key parameters such as process gain (Kp), time constant (τ), and time delay (td) can be extracted [13]. These parameters are then used to calculate the PID tuning constants. The bump test assumes that the system is linear and that the response can be approximated using first-order plus dead-time (FOPDT) models [20].

Key Parameters from Bump Test:

- Process Gain (Kp): Ratio of output change to input change.
- Time Constant (τ): Time for the system to reach 63% of its total change.
- Time Delay (td): Time between the step input and the beginning of the output response.

$$\Delta PV = 4.95 \tag{18}$$

$$\Delta CO = 5$$

$$Kp = \frac{\Delta Pv}{\Delta CO}$$

$$K = \frac{4.95}{5}$$

$$T = 1.5(t_{63\%} - t_{28\%})$$

$$T = 1.5\ (13\ \times 10^{-6} - 8.5\ \times 10^{-6})$$

$$T = 1.5\ (4.5\ \times\ 10^{-6})$$

$$T = 6.75\ \times 10^{-6})$$

$$L =\ t_{63\%} - T$$

$$L = (13\ \times\ 10^{-6}) - (6.75\ \times 10^{-6})$$

$$L = 6.25\ \times\ 10^{-6}$$

$$KP = \frac{1.2\ \times 6.75\ \times\ 10^{-6}}{6.25\ \times\ 10^{-6}\ \times 0.99}$$

$$KP = \frac{0.9}{6.19}$$

$$KP =\ \ 0.145$$

$$Ti = 3.33\ \times L$$

$$Ti = 3.33\ \times 6.25\ \times\ 10^{-6}$$

$$Ti = 20.812\ \times\ 10^{-6}$$

$$Ti = 2.0812\ \times\ 10^{-5}$$

$$Td = 0.5\ L$$

$$Ti = 3.125 \times\ 10^{-6}$$

$$Ki = \frac{KP}{Ti}$$

$$Ki = \frac{0.145}{12.5\ x\ 10^{-6}}$$

$$Ki = \frac{0.0116}{10^{-6}}$$

$$Ki = 0.0116 \times\ 10^{-6}$$

$$Ki = 1{,}16 \times\ 10^{-4}$$

$$Kd = Kp\ x\ Td$$

$$Kd = 0.145\ x\ 3.125\ \times\ 10^{-6}$$

$$Kd = 4.531 \times\ 10^{-7}$$

2.3. Experimental Result

The experimental testing process was conducted by utilizing MATLAB/Simulink in conjunction with an Arduino Uno, serving as a means to verify the results obtained from the simulation [8][29]. MATLAB Simulink was specifically employed as a bridge between the software environment and the hardware components [11], enabling seamless integration for testing purposes. The experimental setup comprised several critical components, including a DC-DC buck converter, a current sensor, a voltage-current sensor, a computer equipped with the MATLAB/Simulink platform, a DC power supply, and an Arduino Uno. The input voltage for the system was set at Vin = 15V, and the experimental response was evaluated based on the duty cycle and the output voltage for a reference voltage of Vref = 5V [32].

The simulation outcomes were compared with the experimental responses of the output voltage for a stepped input voltage. It was observed that the experimental results demonstrated the ability of the system to track the reference voltage, though with minor inaccuracies. Despite these deviations, the system exhibited a remarkably fast response time and a noticeable overshoot in the output voltage.

To further validate the effectiveness and accuracy of the developed controller, additional simulations were carried out using the MATLAB Simulink application. These simulations were based on a circuit configuration designed specifically for this purpose. All the previously calculated parameters, including the RLC component values and PID gain values, were applied to the system during this phase. The resulting outputs from these simulations reflect the system's response under the prescribed conditions, confirming the validity of the design approach. The results, generated directly from MATLAB Simulink, are presented to demonstrate the reliability and robustness of the proposed controller in meeting the desired performance criteria [32].

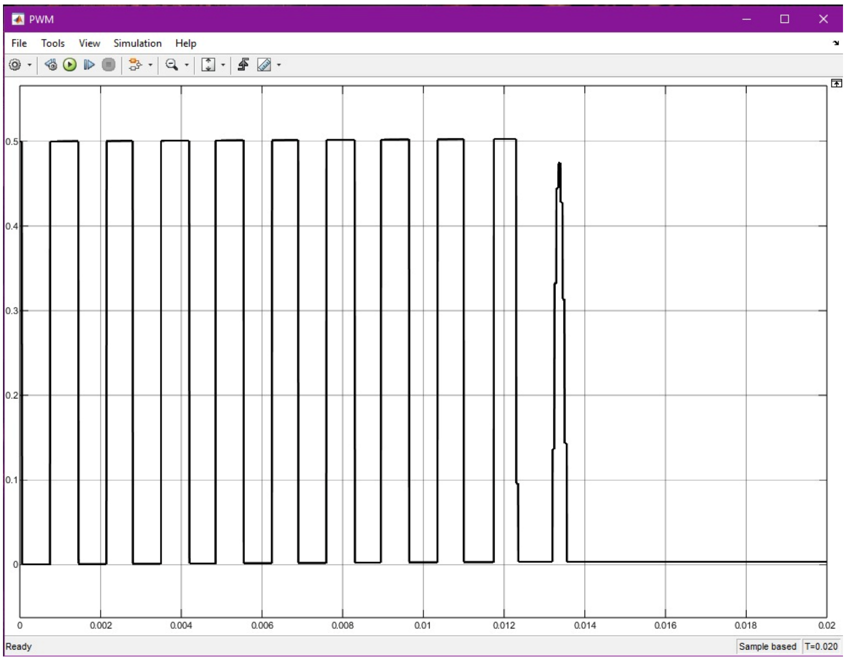


Figure 5: PWM Pulse Width Modulation) Signal.

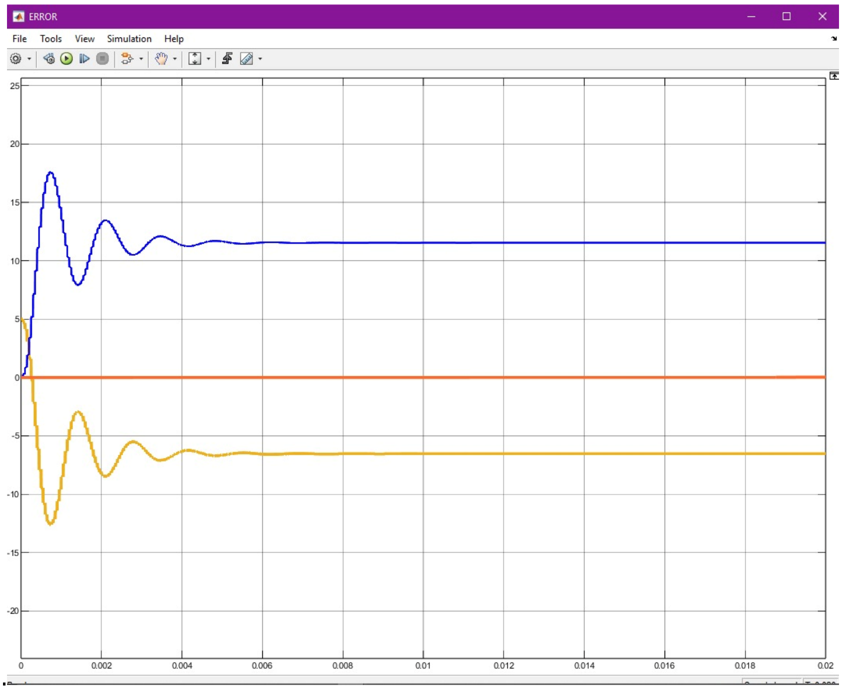


Figure 6: Error Signal.

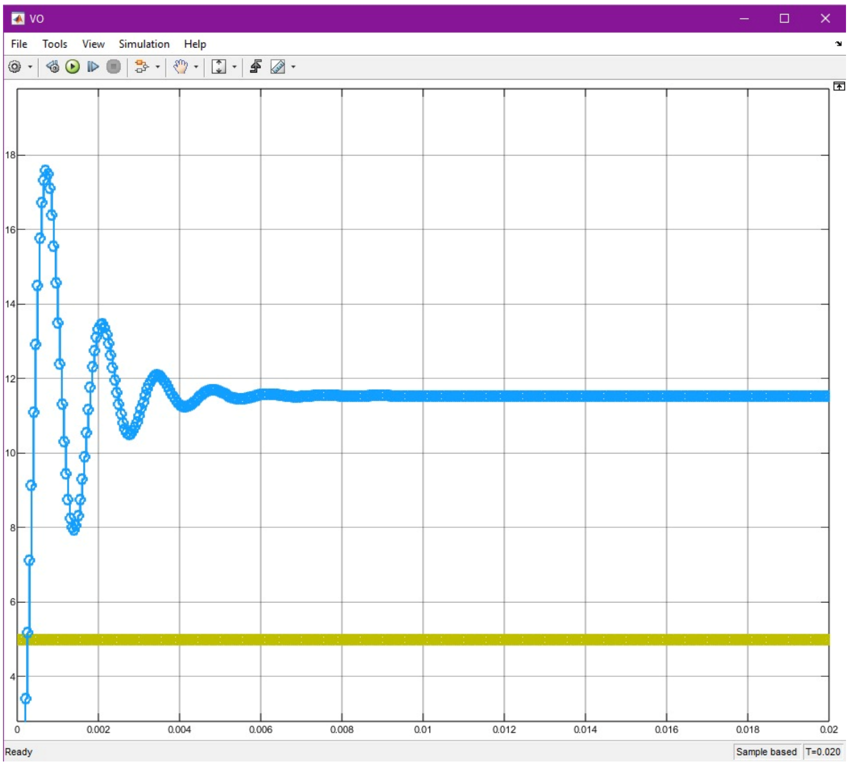


Figure 7: V_O Signal.

Figure 8: Oscilloscope results.

The results of this experiment are largely consistent with the simulations previously conducted using Simulink, demonstrating a high degree of alignment between the theoretical model and the practical implementation. Specifically, with a load resistance of 2.5 Ω the experiment produced an output voltage of 3,6 V. This finding underscores the effectiveness of the simulation in predicting system behavior [4], while also highlighting the minor deviations that may arise due to practical factors such as hardware tolerances, environmental conditions, or measurement inaccuracies [29][11].

- PWM Output (Pulse Width Modulation): The second graph depicts the PWM signal applied to the MOSFET switch in the buck converter. The duty cycle of this signal dynamically adjusts in response to variations in the output voltage, ensuring that the output remains stable at the desired level. The changes in the duty cycle reflect the real-time response of the PID controller, which continuously adapts to maintain effective control of the output voltage. After a brief transient period, the duty cycle stabilizes, indicating the controller's ability to achieve and maintain system stability [8].
- Error Signal: The third graph illustrates the error signal, which represents the difference between the reference voltage and the actual output voltage. Initially, the error is high as the output voltage ramps up toward the target [32]. Over time, the error decreases significantly as the output voltage approaches the set point. Minor oscillations in the error signal correspond to the PWM switching effect, but the PID controller ensures the error remains within a low range, keeping the output voltage close to the reference value.
- Output Voltage (Vo): The initial graph displays the output voltage response of the buck converter. The output voltage quickly reaches approximately 5V, close to the set reference value, with a minor ripple in the steady state. This ripple effect, caused by the PWM switching action, is a typical characteristic of buck converters. The rapid stabilization near the reference value, with minimal steady-state error, demonstrates that the PID controller effectively regulates the output voltage and maintains system stability [29]. The response also exhibits an initial transient behavior with overshoot, which dampens over time as the system reaches a stable state.

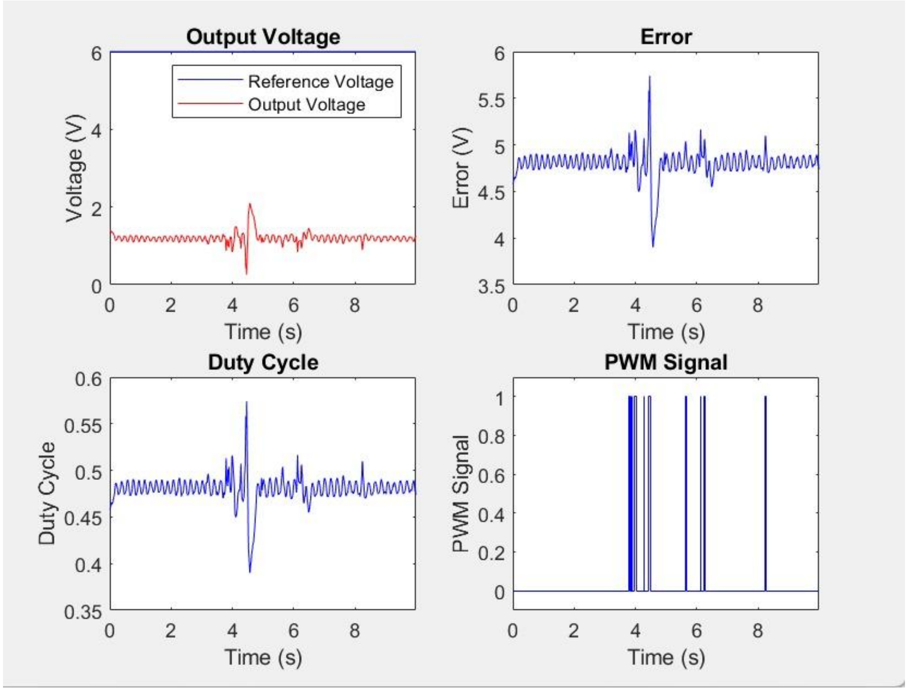


Figure 9: Simulation Result for Voltage References.

The figure above shows the experimental response of the voltage control system to a multi-level reference of 5V. From the results shown, the system demonstrates the ability to dynamically respond to changes in the reference voltage. Although the output voltage has not fully reached the reference value, the system is able to provide a fast response to the change [5], indicated by a spike in the output voltage around time t = 4 seconds.

The error graph illustrates the difference between the reference and output voltage, which is handled by the system through PWM signal adjustment [8]. This can be seen in the duty cycle and PWM signal graphs which undergo active changes when there is a change in the reference. Although the PWM signal has not worked continuously, the resulting pulse pattern reflects the system's effort in stabilizing the output voltage.

This experiment was conducted using the MATLAB/Simulink platform connected to an Arduino Uno. The test circuit consists of a DC-DC buck converter, voltage and current sensors, a computer with MATLAB/Simulink, a USB oscilloscope, and a DC voltage source of 10V. This system shows good potential for further development to optimize the performance of tracking the voltage against the reference.

3. Results and Discussion

3.1. Results

The MATLAB simulation results show that the designed digital PID controller successfully regulates the output voltage stably [17]. **Figure 5** shows the pulse-width modulation (PWM) signal generated by the controller, which is crucial for regulating the output voltage [26]. The PWM signal demonstrates a consistent duty cycle, indicating effective control over the output voltage. **Figure 6** illustrates the error signal between the desired output voltage and the actual output voltage. The error converges to zero rapidly, reflecting the controller's ability to minimize the deviation from the setpoint [34]. This rapid convergence is essential for maintaining system stability. **Figure 7** presents the output voltage of the Arduino-based buck converter. The results indicate that the output voltage stabilizes quickly after a step change in the reference voltage, with minimal overshoot, This behavior is critical in applications where voltage regulation is paramount.

The data collected from these simulations demonstrate that the digital PID controller effectively limits overshoot and ensures output voltage stability under dynamic load conditions. The tuning parameters derived from bump test PID contributed significantly to the controller's performance, allowing for a resilient response to fluctuations in the input and load [34] [17].

The simulation results reveal that the digital PID controller for the DC-DC buck converter successfully achieves a quick response with minimal overshoot [4], which is essential for maintaining output stability despite fluctuations in input voltage and load conditions. During the tuning process, the bump test Arduino-based method was employed to automatically adjust the PID parameters to meet the specified target and gain margins. This approach is particularly effective as it induces oscillations in the system [26], allowing the controller to determine optimal settings without requiring detailed knowledge of the converter's component values or exact dynamic behavior.

The capability to ensure near-optimal performance for various DC-DC buck converter configurations without prior knowledge of system parameters. Furthermore, the performance of bump test PID was compared with traditional tuning techniques in studies focused on advanced control strategies for buck converters, demonstrating that bump test achieves superior stability and dynamic response [19].

The simulation outcomes indicate a controller that is not only responsive but also stable across a range of operating conditions. The rapid response and reduced overshoot are key indicators of a well-tuned PID controller, reinforcing the viability of as an efficient and effective tuning solution in real-world applications involving variable loads and input disturbances [4].

3.2. Discussion

The performance of the digital PID controller was analyzed through various scenarios in MATLAB simulations, focusing on the controller's response to step changes in reference voltage and load disturbances. The results demonstrated that the controller effectively mitigates overshoot and stabilizes output voltage, even with significant load variations [36][17].

The use of the bump test Arduino-based method allowed for a more nuanced approach to tuning, enhancing the controller's robustness against real-world operational challenges [15]. By simulating different load conditions, this study underscores the importance of adaptive control strategies in power electronics, particularly in applications requiring precise voltage regulation [9].

In alignment with other research on practical PID controller applications, such as the air heater control system, the integration of MATLAB, Simulink, and Arduino facilitates reliable parameter tuning and real-time control adjustments [15]. This integration helps to optimize controller performance while ensuring system stability under varying conditions [24][7]. The combination of simulation and experimental validation in this study confirms that bump test provides the necessary robustness and accuracy for industrial control applications, achieving stable output across diverse operating scenarios [36][23].

The findings align with existing literature, which emphasizes the critical role of advanced tuning methods like bump test in optimizing PID controllers for DC-DC converters [18]. The successful implementation of this digital PID controller highlights its potential for improving efficiency and reliability in various electronic systems. Future work could explore the integration of additional control strategies, such as nonlinear control methods, to further enhance performance under varying system dynamics [21].

4. Conclusion

This research successfully developed and implemented a digital PID controller for a DC-DC buck converter using MATLAB. The simulation results demonstrate that this controller can achieve a rapid response with minimal overshoot, which is crucial for maintaining output stability under varying load conditions. Arduino-based bump test PID tuning method proved effective in automatically adjusting the PID parameters, thereby enhancing the controller's robustness and response to input and load fluctuations. The findings indicate that the digital PID controller performs well not only under ideal conditions but also adapts effectively to real-world disturbances. This underscores the importance of digital control techniques in power electronics applications, particularly in the context of precise voltage regulation. This study makes a significant contribution to the understanding and implementation of PID controllers in buck converters and paves the way for further research aimed at optimizing control strategies in various electronic applications. In the subsequent research, the emphasis could be placed on the exploration of alternative control methodologies and the enhancement of the PID tuning process to optimize performance in scenarios that are more intricate and variable.

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