

Research Article

Design, Simulation, and Implementation of a Buck Converter for Efficient DC Voltage Regulation

Md Shawon* , **Sohan Molla** , **Tahrim Fatiha** , **Asif Eakball Emon** ,
Utsa Sen , **Kanij Fatema** 

Department of Electrical & Electronic Engineering, Faculty of Engineering and Applied Sciences, Bangladesh University of Business & Technology (BUBT), Dhaka, Bangladesh

Abstract

The increasing demand for efficient power regulation in embedded systems, renewable energy, and portable electronics has elevated the importance of DC-DC converters in modern power electronics. Among them, the buck converter a type of step-down converter is widely favored due to its high efficiency, compactness, and suitability for low-voltage applications. This study was undertaken to explore the design, simulation, and hardware implementation of a buck converter capable of stepping down a 12 V DC input to output levels of 3 V, 6 V, and 9 V based on duty cycles of 25%, 50%, and 75%, respectively. The objective was to validate theoretical predictions using both simulation and physical testing. The circuit design incorporated essential power electronic components such as IRF9530 MOSFETs, IR2110 driver IC, inductors, capacitors, and freewheeling diodes, assembled on a Vero board for prototype development. Proteus simulation results closely followed expected voltage levels, while hardware testing showed minor deviations due to non-idealities like component tolerances, switching losses, and thermal effects. The comparison between theoretical, simulated, and measured outputs confirmed the operational integrity and efficiency of the design. In addition to the technical focus, this work considers safety measures, ethical responsibility, and environmental impact ensuring the converter's alignment with modern sustainable engineering practices. This project not only demonstrates the functional reliability of buck converters in real-world scenarios but also contributes to students' hands-on learning and fosters innovation in scalable energy systems.

Keywords

Buck Converter, MOSFET Switching, DC-DC Converter, Diodes, Duty Cycle, Efficiency

1. Introduction

The buck converter, also known as a step-down converter, is a fundamental topology in switched-mode power supply (SMPS) systems, widely recognized for its ability to efficiently reduce a higher input voltage to a lower output voltage. Due to its relatively simple design and high efficiency, the buck converter is extensively applied in a variety of domains

including embedded systems, industrial automation, telecommunications, and consumer electronics [1]. Its core operating principle revolves around the rapid switching of a semiconductor device, typically a MOSFET, and the regulated transfer of energy through an inductor-capacitor (LC) network. This project aims to design, simulate, and implement

*Corresponding author: shawon.bubt.bd@gmail.com (Md Shawon)

Received: 20 July 2025; **Accepted:** 1 August 2025; **Published:** 16 August 2025



Copyright: © The Author(s), 2025. Published by Science Publishing Group. This is an **Open Access** article, distributed under the terms of the Creative Commons Attribution 4.0 License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

a functional buck converter capable of stepping down a DC voltage input of 12 V to lower levels determined by varying the duty cycle of a pulse-width modulation (PWM) signal [2]. Theoretical calculations were validated through both simulation and hardware implementation to assess converter performance across different operating conditions. Specifically, output voltages were measured for duty cycles of 25%, 50%, and 75%, confirming expected step-down behavior [3].

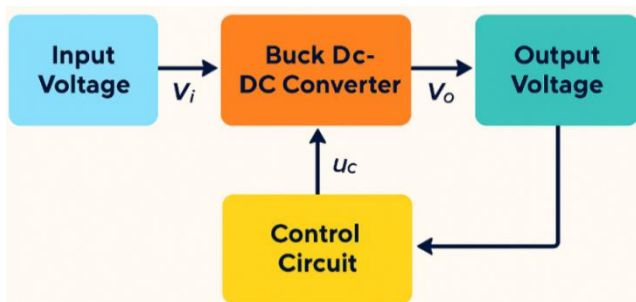


Figure 1. Block Diagram of Buck DC-DC Converter.

The simulation and hardware results demonstrate the converter's functionality, revealing minor deviations in practical implementation due to component non-idealities, switching losses, and thermal effects. These discrepancies are analyzed and compared with theoretical predictions, providing insights into practical design considerations necessary for optimizing converter efficiency and performance. The outcome of this study underscores the viability of the buck converter as a reliable solution for voltage regulation tasks within electronic systems [4].

2. Literature Review

The buck converter, a type of DC-DC step-down power supply, has been extensively researched due to its widespread utility in voltage regulation for various electronics and power systems. Originating from the field of switched-mode power supply (SMPS) design, buck converters continue to play a critical role in both analog and digital power regulation systems. According to Erickson and Maksimović (2001), buck converters operate on the principle of storing and transferring energy through inductive and capacitive elements while modulating the switching duty cycle to regulate output voltage. Their efficiency is typically high often above 85% and, faster switching, and lower conduction losses. These wide-bandgap semiconductors allow higher switching frequencies, reducing the size of passive components and improving transient response. Academic works such as those by Wu et al. (2022) and Huang et al. (2023) have also explored multi-phase buck converters, which distribute current across multiple phases to improve efficiency, thermal management, and current handling in high-load scenarios. Furthermore, integrated magnetic components and

PCB-embedded inductors have been introduced to enhance space efficiency in power modules [5]. Collectively, these advancements reinforce the importance of comprehensive modeling, precise control, and efficient hardware design to achieve optimal performance in buck converter systems, particularly in mission-critical and space-constrained occasionally exceeding 95% due to minimal energy dissipation in ideal conditions. This makes them especially valuable in low-power, high-efficiency applications such as portable electronics and embedded systems [6]. Simulation-based studies, such as those using Spice or MATLAB/Simulink environments, have validated the relationship between duty cycle and output voltage ($V_o = V_{in} \times D$), where V_{in} is the input voltage and D is the duty cycle. Practical work often confirms this behavior under controlled conditions. However, discrepancies between simulation and experimental results arise due to non-ideal characteristics of components, including switching losses, parasitic capacitance, and electromagnetic interference [3]. Describes reduced output impedance in PWM buck converters using genetic algorithms for control optimization [7]. Recent advancements have introduced high-frequency switching and improved control strategies, such as hysteretic and current-mode control, which have further enhanced transient response and reduced output ripple [8]. These improvements enable finer output regulation and system stability under varying load conditions. In practical implementation, researchers have emphasized the importance of accurate component selection and thermal management. For instance, inductor core material and MOSFET switching speed directly affect efficiency and heat dissipation. Moreover, discrepancies observed between simulation and hardware are often attributed to model inaccuracies, component tolerances, and layout-induced parasitic, aligning with findings from prior studies [9]. A Novel Winding-Coupled Buck Converter introduces a high-frequency, high step-down topology achieving over 80% efficiency at 2 MHz switching [10]. Overall, existing research supports the robustness of buck converter theory and affirms the viability of simulation tools for predictive analysis. Nonetheless, careful attention to design limitations and non-ideal parameters remains essential for achieving reliable, high-performance converter systems. In recent years, the evolution of buck converter technologies has been driven by the growing demand for compact, reliable, and energy-efficient power solutions across a wide range of industries. Studies such as those by Rashid (2017) and Mohan et al. (2020) have underscored the buck converter's critical role in modern power architecture, especially in battery-powered devices, Internet of Things (IoT) systems, and renewable energy applications. These studies highlight improvements in converter topologies that enable dynamic voltage scaling, better thermal distribution, and high power density, which are essential for today's miniaturized electronics [11]. Modern buck converters increasingly leverage soft-switching techniques such as Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) to minimize

switching losses and electromagnetic interference (EMI). These methods significantly improve converter efficiency, especially in high-frequency operations. Recent literature also explores digital control strategies, including adaptive and predictive control algorithms implemented through microcontrollers or digital signal processors (DSPs), to enhance regulation precision under dynamic load conditions. Moreover, Gallium Nitride (GaN) and Silicon Carbide (SiC) based devices are becoming popular replacements for traditional silicon MOSFETs due to their superior thermal performance applications.

3. Methodology

The methodology of this study focuses on the design, simulation, and hardware implementation of a buck converter, aimed at demonstrating effective DC-DC voltage step-down functionality based on varying duty cycles. The approach is structured into three main phases: theoretical modeling, simulation, and hardware realization [12].

Figure 2 the flowchart illustrates the complete development process of a buck converter, beginning with the clear definition of the problem designing a circuit to step down DC voltage using a buck converter. It proceeds to the theoretical design phase, where the operating principle is analyzed, and the key voltage relation is derived to guide the expected output behavior. Following this, essential components such as MOSFETs, diodes, inductors, capacitors, and the IR2110 driver are selected and organized for circuit assembly [13]. The simulation testing phase involves assembling the circuit virtually or on a test board, applying a constant 12 V input, and varying the duty cycle to observe the corresponding changes in output voltage [14].

After validating the theoretical performance through simulation, hardware testing is conducted to replicate the conditions in a real-world setup, where the measured output voltages are compared with simulated results to analyze consistency and identify possible deviations due to non-idealities like component tolerances and switching losses. Finally, the project concludes by confirming the buck converter's step-down functionality, ensuring that the system performs efficiently and reliably in practice as it was intended in theory and simulation [2].

The buck converter is a type of DC-DC step-down converter that operates by periodically switching a power transistor to regulate the voltage supplied to a load. Its fundamental operating principle is based on the controlled transfer of energy from the input to the output through an inductor and a switching element. The converter reduces the input voltage by modulating the duty cycle of the switch, making it suitable

for applications that require efficient voltage regulation. When the switch (typically a MOSFET) is turned ON, the inductor is directly connected to the input voltage source [15]. During this phase, current flows through the inductor and energy is stored in its magnetic field. Simultaneously, the diode becomes reverse-biased, preventing current from flowing backward. When the switch is turned OFF, the inductor maintains current flow by releasing stored energy. The diode becomes forward-biased, allowing current to continue flowing through the inductor to the output capacitor and load. The output capacitor helps maintain a steady voltage by smoothing out voltage ripples caused by the switching operation [16].

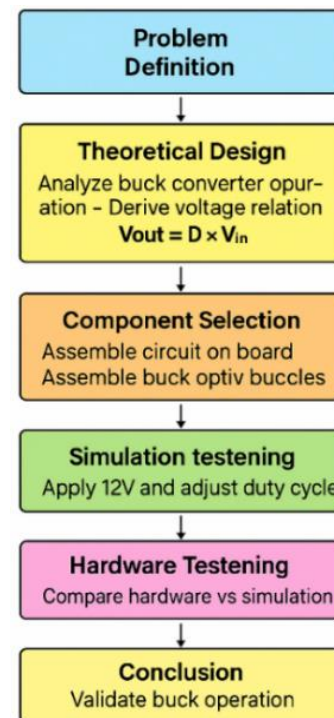


Figure 2. Flowchart of Buck Converter Design and Testing Process.

The relationship between the output voltage V_{OUT} , the input voltage V_{in} , and the duty cycle D (defined as the ratio of the ON time to the total switching period) is given by:

$$V_{OUT} = D \times V_{in} \quad (1)$$

Where, V_{OUT} is the average output voltage, V_{in} is the input supply voltage, D is the duty cycle ($0 \leq D \leq 1$).

For this project, the input voltage was maintained at a constant 12 V. The expected output voltages were calculated using the formula above for varying duty cycles: [13]

$$\text{Capacitor voltage, } \Delta V_C = [V_{IN} \times D_r (1 - D_r)] / 8LC f^2 \quad (2)$$

$$\text{Inductor current } \Delta I_L = [V_{IN} \times D_r (1 - D_r)] / f L \quad (3)$$

$$\text{Maximum and minimum current of inductor, } I_{\text{MAX}} = I_0 + V_0 T_{\text{OFF}} / 2L \quad (4)$$

$$\text{And, } I_{\text{MIN}} = I_0 - V_0 T_{\text{OFF}} / 2L \quad (5)$$

$$\text{Determination of filter inductance, } L = 3.33 V_0 (T_s - T_{\text{ON}}) / I_0 \quad (6)$$

$$\text{Determination of filter capacitance, } \Delta V_C = V_{\text{IN}} D_r (1 - D_r) / 8LCf^2 \quad (7)$$

The buck converter utilizes a variety of components to ensure efficient voltage step-down operation. IRF9530 MOSFETs serve as the main switching devices, controlled by the IR2110 driver IC, which ensures proper gate operation. Two 7805 voltage regulators provide a stable 5V supply for control circuits. Capacitors of various ratings (1 μF , 22 μF , 0.1 nF) are used for filtering and noise suppression, driver, while 820 μH inductors store and release energy during switching cycles. Freewheeling diodes (1N4007) maintain current flow when the switch is off, and 220 Ω resistors are used for current limiting and control. Load resistors simulate real-world operating conditions for testing, and the entire circuit is assembled on a Vero board. Banana plugs and sockets serve as connectors for secure and flexible external connections to power sources and measurement tools [17].

Table 1. List of Components Used in the Buck Converter Design.

Component	Specification	Quantity
MOSFET	IRF9530	2
Driver IC	IR2110	1
Voltage Regulator	7805	2
Capacitors	1 μF , 22 μF , 0.1 nF	Various
Inductor	820 μH	5
Diodes	1N4007	10
Resistors	220 Ω	50
Load Resistors	-	2
PCB / Vero Board	-	1
Connectors	Banana plugs/sockets	Various

4. Results

The flowchart visually represents the theoretical design of a buck converter, outlining its fundamental operating principle. It begins with the concept that the converter operates by

switching a transistor on and off when the switch is on, the inductor stores energy, and when the switch is off, the inductor releases that energy to the load. The relationship between output voltage and duty cycle is defined by the equation V_{OUT} . V_{in} is fixed at 12V. This theoretical framework predicts specific output voltages based on different duty cycles. The diagram effectively shows how controlling the duty cycle adjusts the output voltage, confirming the step-down behavior fundamental to buck converter operation.

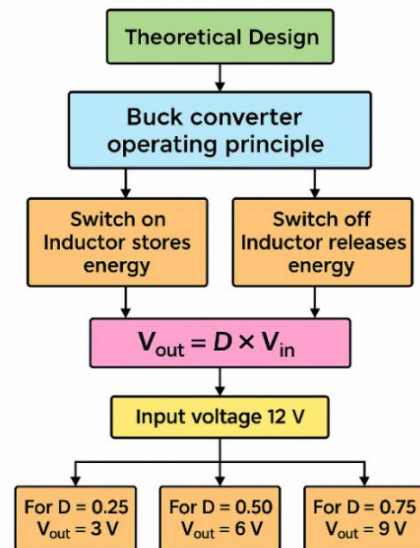


Figure 3. Theoretical Operation of a Buck Converter.

4.1. Simulation

Simulation of the buck converter circuit was performed using proteus software a standard power electronics simulation tool. The simulation included all essential passive and active components a switching MOSFET (IRF9530), an inductor, a freewheeling diode (1N4007), and output filter capacitors. The duty cycles were varied systematically (25%, 50%, 75%) to observe and verify the expected output voltage levels.

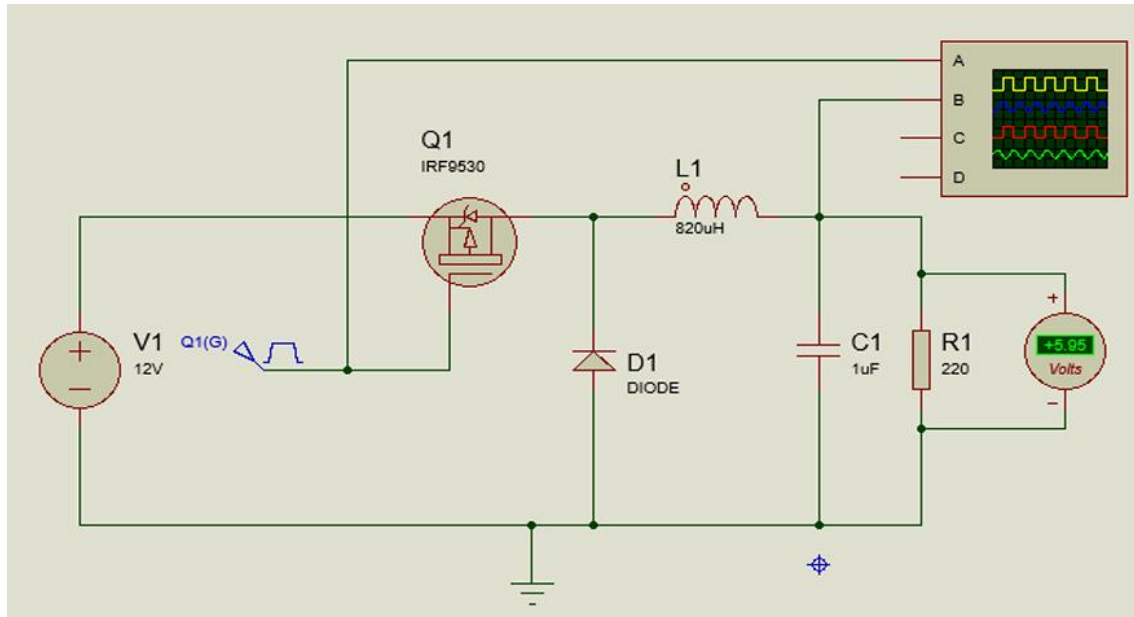
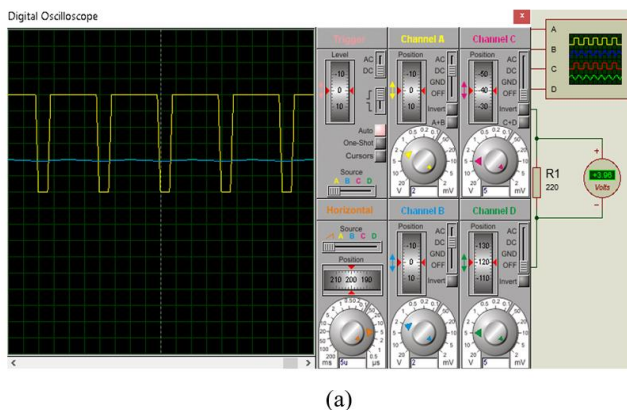


Figure 4. Simulation Buck Converter Circuit Diagram.

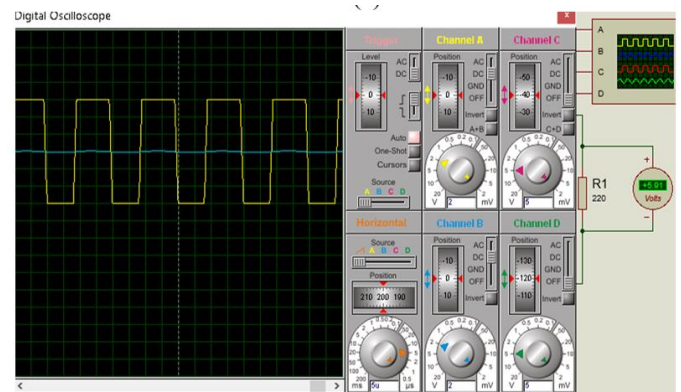
Figure 4 the circuit uses a P-channel MOSFET (IRF9530) labeled Q_1 as the main switching element. The input voltage source (V_1) supplies 12V, and a PWM signal is applied to the gate of Q_1 to control its switching operation. When the MOSFET turns ON, current flows through the inductor (L_1 , 820 μ H), storing energy in its magnetic field. When the MOSFET turns OFF, the freewheeling diode (D_1) becomes forward-biased, and the inductor releases its stored energy through the capacitor (C_1 , 1 μ F) and load resistor (R_1 , 220 Ω). The capacitor smooths out voltage ripples to maintain a stable DC output.

4.2. Simulation Results

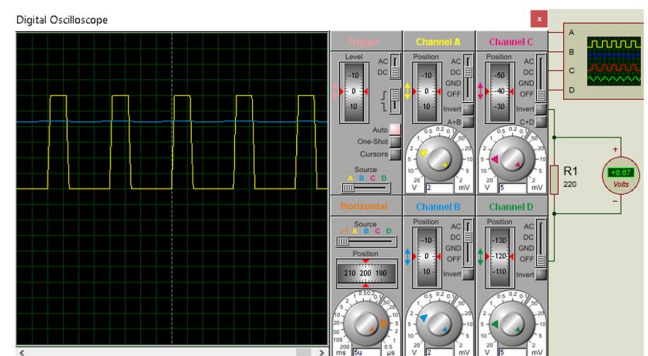
The buck converter circuit was simulated using standard circuit simulation software. The simulations were conducted for three distinct duty cycles, 25%, 50%, and 75%, with an input voltage of 12V maintained consistently throughout all tests.



(a)



(b)



(c)

Figure 5. Simulation Output (a) 25% duty cycle average output voltage and graph (b) 50% duty cycle average output voltage and graph (c) 75% duty cycle average output voltage and graph.

The simulated output voltages were as follows:

Table 2. Comparison of Theoretical, Simulated, and Hardware Output Voltages at Different Duty Cycles.

Duty Cycle	Theoretical Output (V)	Simulated Output (V)	Simulation Output (V)
25%	3.00	3.06	~3.00
50%	6.00	5.91	~6.00

Duty Cycle	Theoretical Output (V)	Simulated Output (V)	Simulation Output (V)
75%	9.00	8.67	~9.00

4.3. Hardware Implementation

The hardware prototype was constructed on a Vero board using commercially available discrete components as per the simulation model.

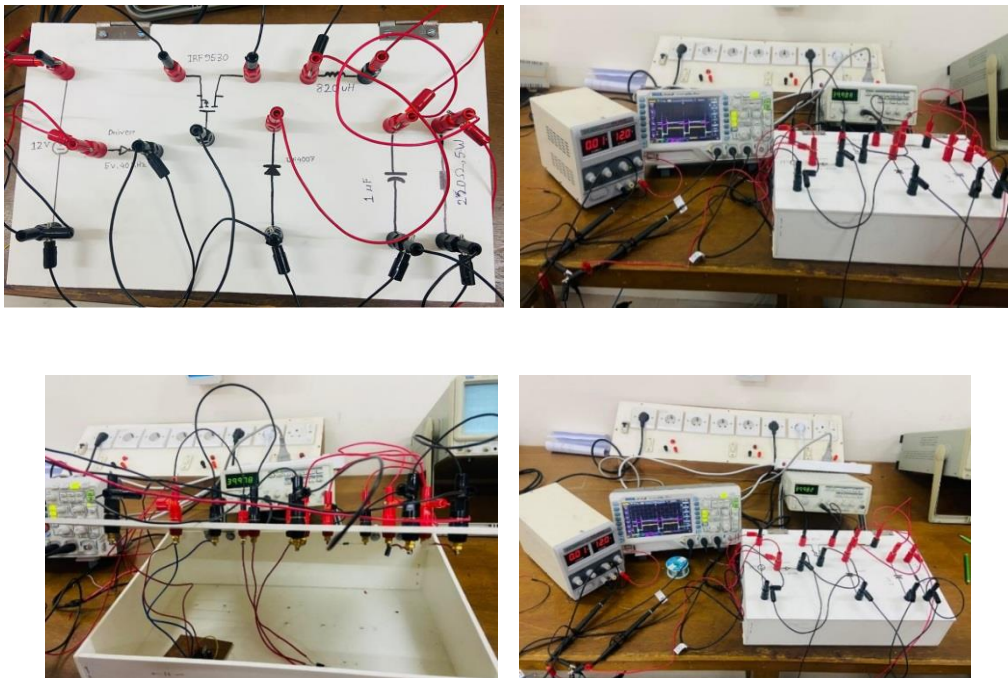
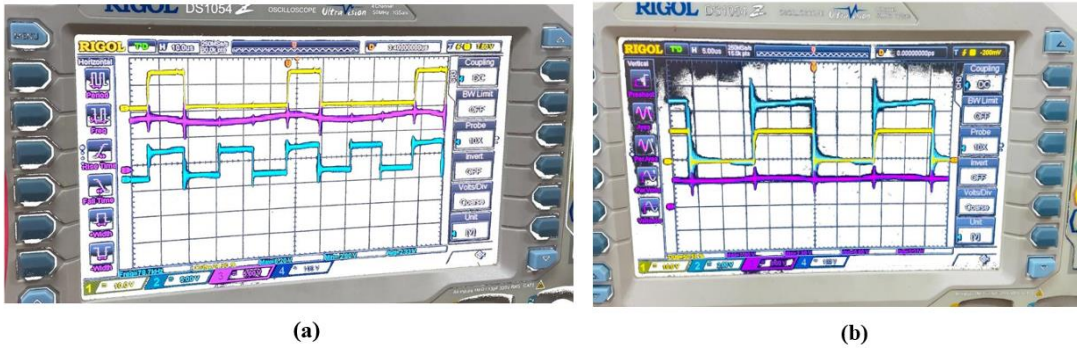
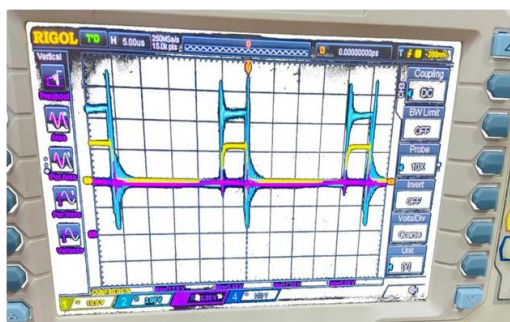


Figure 6. Hardware base buck converter circuit diagram (setup).

4.4. Hardware Result

Connections were securely soldered and enclosed in a protective casing. Oscilloscope readings were obtained at the output terminals to record real-time voltage under various duty cycle settings.





(c)

Figure 7. Hardware base buck converter circuit diagram output. (a) 25% duty cycle (b) 50% duty cycle (c) 75% duty cycle.

The Hardware output voltages:

Table 3. Comparison of Theoretical, Simulated, and Hardware Output Voltages at Different Duty Cycles.

Duty Cycle	Theoretical Output (V)	Simulated Output (V)	Hardware Output (V)
25%	3.00	2.96	~3.00
50%	6.00	5.60	~6.00
75%	9.00	8.37	~9.00

4.5. Expected Result

Based on the theoretical operation of a buck converter, the output voltage is directly proportional to the product of the duty cycle and the input voltage. For a fixed input of 12V, the expected output voltages under ideal conditions are as follows: 3V for a 25% duty cycle, 6V for a 50% duty cycle, and 9V for a 75% duty cycle. These values assume ideal components with no losses, such as zero voltage drop across the diode, no internal resistance in the inductor, and perfect switching behavior of the MOSFET. These outputs serve as reference benchmarks for comparison with both simulation and hardware testing results.

For 25% duty cycle,

Average output voltage $V_o = V_s \times D = 12 \times 0.25 = 3V$ [$D = 25\%$ and $V_s = 12V$]

For 50% duty cycle,

Average output voltage $V_o = V_s \times D = 12 \times 0.50 = 6V$ [$D = 50\%$ and $V_s = 12V$]

For 75% duty cycle,

Average output voltage $V_o = V_s \times D = 12 \times 0.75 = 9V$ [$D = 75\%$ and $V_s = 12V$]

Measured average output voltages under the corresponding duty cycles were. Approximately 3V at 25% duty cycle, approximately 6V at 50% duty cycle, approximately 9V at 75% duty cycle. Although there were minor deviations from the ideal values, these were attributed to non-ideal behavior in physical components, switching losses, and tolerances in

passive elements.

5. Conclusions

This research presented a comprehensive approach to the design, simulation, and hardware implementation of a buck converter aimed at efficient DC voltage regulation. The converter was developed to step down a constant 12V input to output levels of approximately 3V, 6V, and 9V, corresponding to duty cycles of 25%, 50%, and 75%, respectively. Through theoretical modeling, circuit simulation using Proteus, and real-world hardware testing, the study validated the expected operational characteristics of the converter. Simulation results demonstrated close agreement with theoretical calculations, while hardware testing revealed minor deviations primarily attributed to non-idealities in physical components, switching losses, and thermal effects. Nonetheless, the converter consistently exhibited stable and predictable voltage regulation behavior, confirming the accuracy of the design and its suitability for practical applications. Beyond the technical achievements, the study incorporated considerations of safety, ethical responsibility, and environmental impact, aligning with best practices in sustainable engineering. The work also provided a valuable educational platform, enhancing practical skills and conceptual understanding among students engaged in the project. The findings affirm the effectiveness of the buck converter for use in embedded systems, renewable energy systems, and consumer electronics requiring reliable step-down voltage conversion. The results contribute to the broader field of power electronics by offering a validated reference design and implementation methodology. Future research may focus on incorporating advanced control strategies, higher switching frequencies, and wide-bandgap semiconductor technologies to further improve performance, efficiency, and integration in compact power management solutions.

Abbreviations

DC Direct Current

AC	Alternating Current
PWM	Pulse Width Modulation
SMPS	Switched-Mode Power Supply
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
IC	Integrated Circuit
DSP	Digital Signal Processor
EMI	Electromagnetic Interference
ZVS	Zero Voltage Switching
ZCS	Zero Current Switching
GaN	Gallium Nitride
SiC	Silicon Carbide
Vo	Output Voltage
Vin	Input Voltage
IoT	Internet of Things
PCB	Printed Circuit Board
IR	International Rectifier (used in IC and MOSFET Model Names like IR2110, IRF9530)

Author Contributions

Md Shawon: Conceptualization, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Writing - original draft, Writing - review & editing

Sohan Molla: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Writing - original draft

Tahrim Fatiha: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Resources, Visualization, Writing - original draft, Writing - review & editing

Asif Eakball Emon: Conceptualization, Formal Analysis, Funding acquisition, Investigation, Visualization

Utsa Sen: Conceptualization, Data curation, Funding acquisition, Investigation, Resources, Visualization, Writing - review & editing

Kanij Fatema: Supervision, Review, Formal Analysis, Investigation, Methodology

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] Md. Fahim Hasan Khan, Sadman Sakib, Md. Ashiqur Rahman, and Md. Zamilur Reza, "DC-DC and AC-DC Zeta and Buck Converter Design and Analysis for High Efficiency Application," 2017, <https://doi.org/10.13140/RG.2.2.32613.09444/3>
- [2] B. A. Altug, A. Kababiyik, E. Dincol, and C. Batunlu, "Buck Converter with Optocoupler Based Switching," in *2021 8th International Conference on Electrical and Electronics Engineering (ICEEE)*, Antalya, Turkey: IEEE, Apr. 2021, pp. 184-190. <https://doi.org/10.1109/iceee52452.2021.9415957>
- [3] "Digital control strategies of DC-DC converters in automotive hybrid powertrains," in *Modeling, Operation, and Analysis of DC Grids*, Elsevier, 2021, pp. 245-287. <https://doi.org/10.1016/b978-0-12-822101-3.00015-0>
- [4] H. Sucu, T. Göktaş, and M. Arkan, "Design, Simulation and Application of Buck Converter with Digital PI Controller," *Balk. J. Electr. Comput. Eng.*, vol. 9, no. 2, pp. 106-113, Apr. 2021, <https://doi.org/10.17694/bajece.884290>
- [5] M. Abolghasemi, I. Soltani, M. Shivaie, and H. Vahedi, "Recent advances of step-up multi-stage DC-DC converters: A review on classifications, structures and grid applications," *Energy Rep.*, vol. 13, pp. 3050-3081, Jun. 2025, <https://doi.org/10.1016/j.egyr.2025.02.025>
- [6] "Current Programmed Control," in *Fundamentals of Power Electronics*, Boston, MA: Springer US, 2001, pp. 439-487. https://doi.org/10.1007/0-306-48048-4_12
- [7] F. Asadi, "Reduction of Output Impedance of Buck Converter with Genetic Algorithm," *Balk. J. Electr. Comput. Eng.*, vol. 10, no. 3, pp. 317-322, Jul. 2022, <https://doi.org/10.17694/bajece.1096188>
- [8] Jingquan Chen, D. Maksimovic, and R. W. Erickson, "Analysis and design of a low-stress buck-boost converter in universal-input PFC applications," *IEEE Trans. Power Electron.*, vol. 21, no. 2, pp. 320-329, Mar. 2006, <https://doi.org/10.1109/tpel.2005.869744>
- [9] C. Jiang, C. Chai, Y. Yang, Y. Liu, and Y. Yang, "An IAOT controlled current-mode buck converter with RC-based inductor current sensor," *IEICE Electron. Express*, vol. 17, no. 4, pp. 20190757-20190757, 2020, <https://doi.org/10.1587/elex.17.20190757>
- [10] K. Yao, Y. Qiu, M. Xu, and F. C. Lee, "A Novel Wind-up-Coupled Buck Converter for High-Frequency, High-Step-Down DC-DC Conversion," *IEEE Trans. Power Electron.*, vol. 20, no. 5, pp. 1017-1024, Sep. 2005, <https://doi.org/10.1109/tpel.2005.854022>
- [11] R. Singh, V. Kurukuru, and M. Khan, "Advanced Power Converters and Learning in Diverse Robotic Innovation: A Review," *Energies*, vol. 16, no. 20, p. 7156, Oct. 2023, <https://doi.org/10.3390/en16207156>
- [12] P. Alavi, E. Babaei, P. Mohseni, and V. Marzang, "Study and analysis of a DC-DC soft - switched buck converter," *IET Power Electron.*, vol. 13, no. 7, pp. 1456-1465, May 2020, <https://doi.org/10.1049/iet-pel.2019.0431>
- [13] "Computational Investigation of Cs2BiAgI6 for Perovskite Solar Cell Applications Using SCAPS-1D," *J. Sustain. Dev. Innov.*, vol. 2, no. 2, 2025, <https://doi.org/10.61552/jsi.2025.02.003>
- [14] S. Molla, M. Shawon, M. Nawaj, and A. Emon, "Analysis of Aging Effect and Cell Balancing Problem of Lithium-Ion Battery," *J. Electr. Electron. Eng.*, vol. 13, no. 2, pp. 92-107, Mar. 2025, <https://doi.org/10.11648/j.jeee.20251302.11>

- [15] D. G. Aller, D. G. Lamar, J. R. Garc ía-Mere, M. Arias, J. Rodriguez, and J. Sebastian, "Performance Evaluation of the Two-Input Buck Converter as a Visible Light Communication High-Brightness LED Driver Based on Split Power," *Sensors*, vol. 24, no. 19, p. 6392, Oct. 2024, <https://doi.org/10.3390/s24196392>
- [16] S. Masri, N. Mohamad, and M. H. M. Hariri, "Design and development of DC-DC buck converter for photovoltaic application," in *2012 International Conference on Power Engineering and Renewable Energy (ICPERE)*, Bali, Indonesia: IEEE, Jul. 2012, pp. 1-5. <https://doi.org/10.1109/icpere.2012.6287236>
- [17] A. Emon, M. Shawon, S. Molla, and M. Nowjh, "Improved Microgrid Controller with Robust Stability, Conjunction with PID Controllers," *J. Electr. Electron. Eng.*, vol. 13, no. 3, pp. 116-130, May 2025, <https://doi.org/10.11648/j.jeee.20251303.11>