

Design and Implementation of a Digital PWM Based DC-DC Voltage Regulation System for Electric Vehicle

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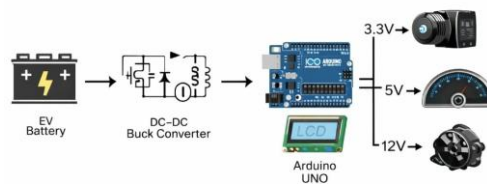
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ABSTRACT: Electric Vehicles (EVs) require stable auxiliary power supplies to operate electronic subsystems such as controllers, sensors, communication modules, and display units. However, fluctuations in the EV battery voltage due to load variations may affect the reliable operation of these sensitive electronic components. To overcome this issue, a digitally controlled DC-DC voltage regulation system is proposed. In this project, a PWM-based closed-loop buck converter is implemented using an Arduino UNO. The system is designed to operate with an EV battery as the primary DC input source. A discrete buck converter consisting of a MOSFET, inductor, diode, and capacitor is used as the power stage to step down and regulate the voltage. The output voltage is sensed through a voltage divider circuit and fed to the Arduino ADC for feedback control. The system can generate selectable output voltages such as 3.3V, 5V, and 12V, which are commonly used in EV electronic subsystems. For demonstration, components such as LED indicators and a buzzer are connected as loads representing devices operating at these voltage levels. The output voltage can also be modified through software programming, making the system flexible and user configurable for different voltage requirements. Based on the selected reference voltage, the Arduino adjusts the PWM duty cycle to maintain the required output. The regulated voltage is displayed on an LCD for real-time monitoring. The proposed system demonstrates a flexible, user-efficient, and digitally controlled auxiliary voltage regulation system for EV applications.

KEYWORDS: DC-DC Converter, Buck Converter, PWM control, Electric Vehicles, Voltage Regulation, Closed-loop control



I. INTRODUCTION

Electric Vehicles (EVs) have emerged as a promising solution to reduce greenhouse gas emissions and dependence on fossil fuels. Unlike conventional vehicles, EVs rely entirely on electrical energy stored in batteries to power both propulsion systems and auxiliary electronic subsystems. The rapid growth of EV technology has increased the demand for efficient and reliable power management systems. In an EV, the main battery provides a high-voltage DC supply, which is used for driving the traction motor. However, several low-voltage auxiliary subsystems such as Electronic Control Units (ECUs), sensors, communication modules, infotainment systems, and display units require regulated and stable DC voltage levels, typically 3.3V, 5V, and 12V. These subsystems are highly sensitive to voltage variations and require precise voltage regulation for proper functioning.

The EV battery voltage is not constant and varies depending on operating conditions such as acceleration, regenerative braking, load changes, and state of charge. These variations can introduce voltage fluctuations in the auxiliary power



supply, leading to instability, malfunction, or reduced performance of electronic components. Therefore, an efficient DC–DC voltage regulation system is essential to ensure stable operation of auxiliary systems. Conventional DC–DC converters used in EV applications are typically based on analogy control techniques and provide fixed output voltages. Although these systems are widely used, they offer limited flexibility, lack real-time monitoring capabilities, and are not easily adaptable for different voltage requirements. With the advancement of embedded systems, digital control techniques have gained attention due to their flexibility, programmability, and improved control performance.

In this work, a digitally controlled DC–DC buck converter is proposed for EV auxiliary voltage regulation. The system utilizes an Arduino UNO microcontroller to generate PWM signals and implement closed-loop control. A discrete buck converter consisting of a MOSFET, inductor, diode, and capacitor is used as the power stage to step down the input voltage. The proposed system provides selectable output voltage levels of 3.3V, 5V, and 12V, enabling it to support various EV subsystems such as communication modules, control units, and auxiliary loads. The output voltage is continuously monitored using a feedback circuit, and the PWM duty cycle is dynamically adjusted to maintain stable output voltage under varying input conditions. Furthermore, the system offers user-level configurability, allowing output voltage selection through software and switch inputs. This enhances flexibility and makes the system suitable for experimental and real-world EV applications. The main contribution of this work is the design and implementation of a low-cost, digitally controlled, and flexible voltage regulation system that demonstrates effective closed-loop performance for EV auxiliary applications.

RELATED WORK

Recent advancements in Electric Vehicle (EV) power systems have emphasized the importance of efficient DC–DC converters for voltage regulation and power management. DC–DC converters are widely used to interface high-voltage battery systems with low-voltage auxiliary loads such as ECUs, sensors, and communication modules. Conventional EV systems primarily employ buck, boost, and bidirectional DC–DC converters for energy conversion. Among these, buck converters are commonly used for stepping down battery voltage to required levels. Studies have shown that the output voltage of such converters is directly dependent on the duty cycle of the switching device, making Pulse Width Modulation (PWM) a widely adopted control technique.

In existing literature, analog control methods such as PID and voltage-mode control are predominantly used due to their simplicity and reliability. However, these methods often require complex tuning and lack adaptability to dynamic conditions in EV systems. Recent research has focused on digital control techniques using microcontrollers and DSPs, which offer improved flexibility, programmability, and real-time monitoring. Digital PWM control enables adaptive voltage regulation under varying input conditions and load disturbances.

Furthermore, modern EV architectures incorporate bidirectional DC–DC converters to enable energy flow in both directions, especially in regenerative braking systems. Advanced semiconductor devices such as Silicon Carbide (SiC) and Gallium Nitride (GaN) are also being explored to improve efficiency and switching performance. Despite these advancements, most existing systems are complex, costly, and designed for high-power applications, making them less suitable for low-cost prototype implementation and educational purposes.

Therefore, this project focuses on a simplified digital PWM-based buck converter, which provides stable, selectable output voltages for EV auxiliary applications while maintaining low cost and ease of implementation.

II. LITERATURE SURVEY

DC–DC converters play a critical role in modern power electronics for efficient voltage regulation. Conventional buck converters typically employ analog control techniques such as voltage-mode control and current-mode control, which provide stable output but lack flexibility and programmability.

Recent advancements focus on digital control methods using microcontrollers and digital signal processors (DSPs). Digital Pulse Width Modulation (PWM) control enhances system adaptability, enables real-time monitoring, and improves dynamic response under varying load conditions.

In Electric Vehicle (EV) applications, auxiliary DC–DC converters are widely used to step down high battery voltage to regulated low-voltage levels such as 12V, 5V, and 3.3V for electronic subsystems including ECUs, sensors, and communication modules. However, most existing systems provide fixed output voltages and lack user-configurable control.



Therefore, there is a need for a flexible, low-cost, and digitally controlled voltage regulation system capable of providing multiple selectable output voltages with closed-loop control.

III. EXISTING METHODOLOGY

In Electric Vehicle (EV) systems, auxiliary power requirements are typically fulfilled using conventional DC–DC conversion techniques. Most existing systems employ analog-controlled buck converters to step down the high-voltage battery output to required lower voltage levels such as 12V, 5V, and 3.3V. These converters use fixed control circuits such as voltage-mode or current-mode control, which rely on analog components like operational amplifiers and feedback networks. In addition, many EV subsystems utilize dedicated regulator ICs and fixed PWM controller circuits to maintain stable output voltage. For low-power applications, linear voltage regulators are commonly used due to their simplicity; however, they suffer from poor efficiency and high power loss. While switching regulators provide better efficiency, they are generally designed for fixed output voltages and do not support dynamic voltage selection. Furthermore, existing methods offer limited monitoring and control capability, as they lack programmability and real-time adaptability. The output voltage is usually predefined and cannot be easily modified based on system requirements. In EV environments, where battery voltage fluctuates due to acceleration and load variations, these traditional systems may not respond effectively to maintain stable auxiliary voltage.

Therefore, although existing methodologies are reliable and widely used, they lack flexibility, user configurability, and intelligent control, which are essential for modern EV power management systems.

IV. SYSTEM ARCHITECTURE

A. Overview

The proposed system is a digitally controlled DC–DC voltage regulation system designed for Electric Vehicle (EV) auxiliary applications. It integrates both hardware and software components to achieve stable and selectable output voltages under varying input conditions. The system operates in a closed-loop configuration, where the output voltage is continuously monitored, compared with a reference value, and adjusted using Pulse Width Modulation (PWM). This ensures reliable voltage regulation for EV subsystems such as sensors, control units, and communication modules.

B. Hardware Platform

The hardware architecture consists of a DC input source, a discrete buck converter, a voltage sensing unit, a microcontroller, and user interface components. The DC input source, which can be an EV battery or a simulated DC supply, provides the input voltage to the system. The discrete buck converter, comprising a MOSFET, inductor, diode, and capacitor, performs the step-down voltage conversion. The output voltage is then passed through a voltage divider circuit to scale it within the acceptable range of the Arduino UNO ADC. The Arduino UNO acts as the control unit, processing the feedback signal and generating the required PWM signal. Push-button switches are used to select the desired output voltage levels such as 3.3V, 5V, and 12V. A 16×2 I2C LCD display is used to monitor the selected voltage and the regulated output voltage in real time. The load represents EV auxiliary systems, ensuring practical validation of the design.

C. Software Platform

The software architecture is implemented using the Arduino IDE and is responsible for real-time control of the system. Initially, the microcontroller initializes all peripherals including ADC, PWM, LCD, and input switches. The system continuously reads the output voltage using the ADC and converts it into an actual voltage value. This measured voltage is compared with the selected reference voltage, and the error is calculated as the difference between them. Based on this error, the control logic adjusts the PWM duty cycle—if the output voltage is lower than the reference, the duty cycle is increased, and if it is higher, the duty cycle is decreased. This dynamic adjustment ensures that the output voltage remains stable despite variations in input voltage or load conditions. The updated voltage values and selected mode are displayed on the LCD. This process runs continuously, forming a closed-loop control system that guarantees efficient and stable voltage regulation.



V. PROPOSED METHODOLOGY

The proposed system presents a digitally controlled PWM-based closed-loop DC–DC buck converter designed for auxiliary voltage regulation in Electric Vehicle (EV) applications. The primary objective of the system is to provide stable and selectable low-voltage outputs (3.3V, 5V, and 12V) from a fluctuating DC input source that represents an EV battery. The system operates by supplying a DC input voltage to a discrete buck converter, which serves as the main power conversion stage. The buck converter is constructed using a MOSFET as the switching element, an inductor for energy storage, a diode for freewheeling current flow, and a capacitor for output voltage smoothing. This configuration enables efficient step-down conversion of the input voltage to the desired output level. To achieve precise voltage regulation, a closed-loop feedback mechanism is implemented. The output voltage is continuously monitored using a voltage divider circuit, which scales the voltage to a level suitable for the Arduino UNO’s Analog-to-Digital Converter (ADC). The Arduino reads this feedback voltage and converts it into a digital value for processing.

The system allows user-defined voltage selection through push-button switches, enabling the selection of predefined reference voltages such as 3.3V, 5V, and 12V. This feature enhances system flexibility and demonstrates adaptability for different EV auxiliary subsystems, including communication modules, control units, and low-power loads. The Arduino UNO acts as the central control unit and executes the control algorithm. It continuously compares the sensed output voltage with the selected reference voltage and calculates the error between them. Based on this error, the controller dynamically adjusts the PWM duty cycle generated at the output pin. If the output voltage falls below the reference value, the duty cycle is increased, allowing more energy to be transferred through the inductor to the load. Conversely, if the output voltage exceeds the reference value, the duty cycle is reduced, thereby decreasing the output voltage. This real-time adjustment forms a closed-loop control system, ensuring that the output voltage remains stable despite variations in input voltage or load conditions. Additionally, the system includes an LCD display module to provide real-time monitoring of the selected reference voltage and the actual output voltage. This improves user interaction and helps in validating system performance during operation. Overall, the proposed methodology demonstrates a simple, cost-effective, and flexible digital control approach for voltage regulation in EV auxiliary systems. By integrating hardware power electronics with software-based control, the system effectively maintains stable output voltage and showcases the practical implementation of closed-loop PWM control in power electronic applications.

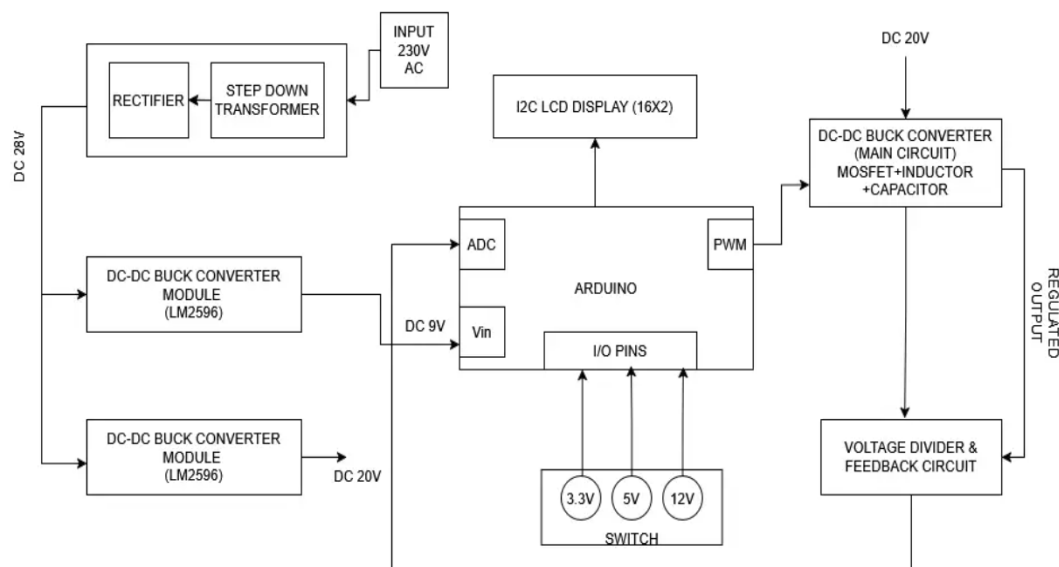


Fig.1. Proposed System Block Diagram



METHODOLOGY EQUATIONS

The proposed system employs a PWM-based closed-loop control strategy to regulate the output voltage of the DC–DC buck converter. The control mechanism is based on the relationship between the PWM duty cycle and the output voltage, along with real-time feedback from the system.

The output voltage of the buck converter is directly dependent on the applied PWM duty cycle, and hence can be expressed as:

$$V_{out} \propto D$$

where V_{out} represents the output voltage and D denotes the duty cycle of the PWM signal. An increase in duty cycle results in a higher output voltage, while a decrease leads to a reduction in output voltage.

To achieve closed-loop control, the system continuously compares the measured output voltage with a predefined reference voltage. The error signal is calculated as:

$$\text{Error} = V_{ref} - V_{out}$$

Where V_{ref} is the selected reference voltage (3.3V, 5V, or 12V), and V_{out} is the sensed output voltage. Based on the calculated error, the PWM duty cycle is adjusted dynamically using a proportional control approach:

$$D_{new} = D_{old} + k \times (V_{ref} - V_{out})$$

where k is a proportional gain constant that determines the rate of adjustment.

In practical implementation, the control logic follows a simple decision-based approach. When the output voltage is lower than the reference, the duty cycle is increased, and when the output voltage exceeds the reference, the duty cycle is decreased. This continuous adjustment ensures that the output voltage is maintained at the desired level.

Thus, the combination of error-based feedback and PWM duty cycle modulation forms a closed-loop voltage regulation system, enabling stable and reliable operation under varying input and load conditions.

VI. RESULTS AND DISCUSSION

The proposed digital PWM-based DC–DC buck converter was experimentally implemented and tested under different operating conditions to evaluate its performance in regulating auxiliary voltages for EV applications. The system was tested for three selectable output voltage levels: 3.3V, 5V, and 12V. The experimental results show that the system successfully maintains a stable output voltage for all selected levels. The Arduino-based closed-loop control continuously monitors the output voltage and dynamically adjusts the PWM duty cycle to minimize the error between the reference and actual output voltage. The performance of the system is summarized in Table 1.

Table 1 : Output Voltage Performance

Selected Voltage	Output Voltage	Status
3.3V	Stable	Regulated
5V	Stable	Regulated
12V	Stable	Regulated

The system demonstrates a fast response to changes in voltage selection and maintains regulation under minor input variations. The PWM duty cycle adapts in real time, ensuring that the output voltage remains within the desired range. The use of a voltage divider feedback circuit and ADC-based sensing improves accuracy and stability.

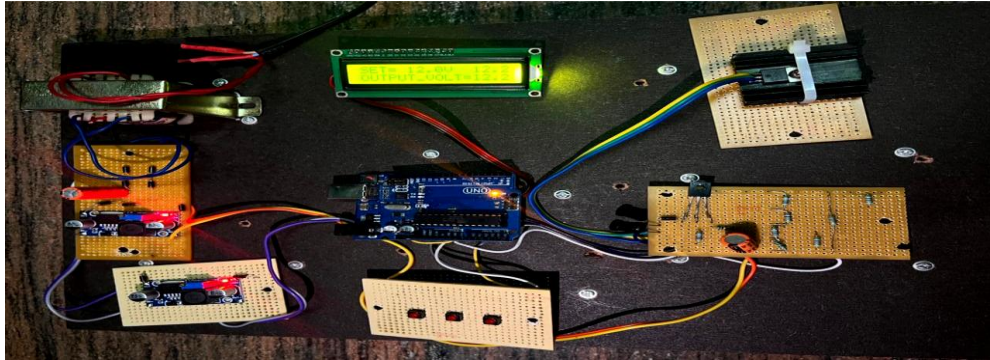


Fig.1.Hardware Setup



Fig.2.Output Voltage display on LCD

D. Discussion

The results confirm that the proposed system effectively implements closed-loop voltage regulation using a simple proportional control method. Compared to conventional fixed-output converters, the system provides flexibility through selectable output voltages and digital control.

Although the system performs well under laboratory conditions, minor variations may occur due to switching losses, component tolerances, and measurement limitations. Additionally, the absence of advanced control techniques such as PID may slightly affect precision under rapid load changes. However, for auxiliary EV applications, the performance is satisfactory and reliable.

VII. CONCLUSION

In this work, a digital PWM-based DC–DC buck converter has been successfully designed and implemented for auxiliary voltage regulation in Electric Vehicle (EV) applications. The primary objective of the system was to provide stable and selectable low-voltage outputs from a varying DC input source, simulating real EV battery conditions. The proposed system effectively addresses the challenges associated with voltage fluctuations in EV auxiliary systems by employing a closed-loop control mechanism. The system integrates a discrete buck converter power stage with an Arduino UNO-based digital controller. The use of a voltage divider for feedback sensing and ADC-based measurement enables accurate monitoring of the output voltage. Based on the difference between the reference and measured voltages, the controller dynamically adjusts the PWM duty cycle, thereby maintaining a regulated output. The



implementation of a simple proportional control strategy ensures reliable operation while keeping the system design cost-effective and easy to implement.

Experimental results demonstrate that the system is capable of maintaining stable output voltages of 3.3V, 5V, and 12V under varying input conditions. The system exhibits good regulation performance, quick response to voltage selection changes, and consistent operation across different modes. The inclusion of a user interface through push-button selection and LCD display enhances system usability and provides real-time monitoring capabilities.

Compared to conventional analog-controlled converters, the proposed system offers significant advantages such as flexibility, programmability, and real-time adaptability. The ability to modify output voltage through software control makes it suitable for a wide range of EV auxiliary subsystems, including sensors, communication modules, and control units. Although the system demonstrates effective performance, it is primarily developed as a prototype and may require further optimization for high-power EV applications. Factors such as switching losses, component tolerances, and efficiency can be further improved using advanced control techniques and optimized hardware design.

Overall, the proposed system presents a simple, cost-effective, and scalable solution for auxiliary voltage regulation in EV systems. It also highlights the practical implementation of digital control techniques in power electronics and provides a strong foundation for future developments in EV power management systems.

VIII. FUTURE SCOPE

The proposed system can be further enhanced to improve performance and applicability in real-world EV systems. Future developments may include:

- Integration with a real EV battery system instead of a laboratory DC source
- Implementation of bidirectional DC–DC converters for energy recovery and regenerative braking
- Use of high-frequency PWM control to improve efficiency and reduce component size
- Adoption of automotive-grade microcontrollers for enhanced reliability
- Incorporation of protection mechanisms such as overcurrent, overvoltage, and thermal protection
- Development of a compact PCB design for practical deployment in EV systems

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