
INTELLIGENT SLIDING MODE CONTROL OF HIGH-GAIN BIDIRECTIONAL DC–DC CONVERTERS FOR MODERN ELECTRIC VEHICLES

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ABSTRACT

The increasing demand for efficient and sustainable transportation has accelerated the adoption of electric vehicles (EVs), where effective power management plays a crucial role in overall system performance. A high-gain bidirectional DC–DC converter (HGBDC) is a key component that facilitates efficient energy transfer between the battery and the motor, particularly during motoring and regenerative braking operations. This work presents a comparative analysis of three control strategies—Proportional–Integral–Derivative (PID), Artificial Neural Network (ANN), and Sliding Mode Control (SMC)—applied to the HGBDC in EV applications. The PID controller offers simplicity and acceptable steady-state performance but struggles under nonlinear and dynamic conditions. The ANN controller improves adaptability and transient response through learning capability, though it introduces computational complexity and training requirements. In contrast, the SMC technique demonstrates superior robustness, faster dynamic response, and improved stability under varying operating conditions and system uncertainties. The proposed system is modeled and simulated using MATLAB/Simulink to evaluate performance in both forward motoring and regenerative braking modes. Comparative results indicate that SMC significantly reduces overshoot, settling time, and oscillations while enhancing efficiency. Hence, SMC is identified as the most effective control strategy for high-gain bidirectional converters in modern electric vehicle powertrains.

Keywords: Electric Vehicles, High-Gain Bidirectional DC-DC Converter, Sliding Mode Control, PID Controller, Artificial Neural Network, Regenerative Braking, MATLAB/Simulink Simulation

INTRODUCTION

The rapid growth of global transportation demand has intensified concerns regarding environmental pollution, fossil fuel depletion, and energy sustainability. Conventional internal combustion engine vehicles significantly contribute to greenhouse gas emissions and air quality degradation, prompting the transition toward cleaner alternatives such as electric vehicles (EVs) [1]. EVs offer advantages including zero tailpipe emissions, higher energy efficiency, and reduced dependence on fossil fuels, making them a promising solution for sustainable mobility [2]. Governments and industries worldwide are actively promoting EV adoption through policies, incentives, and technological advancements. However, the efficient operation of EVs relies heavily on advanced power electronic systems and energy management strategies that can handle dynamic driving conditions [3].

At the core of EV technology lies the battery energy storage system, which supplies power to the electric motor and other auxiliary components. Lithium-ion batteries are widely preferred due to their high energy density, long cycle life, and fast charging capabilities [4]. One of the key features of EVs is regenerative braking, where the kinetic energy of the vehicle is converted back into electrical energy and stored in the battery [5]. This process significantly improves overall energy efficiency and extends the driving range. However, efficient implementation of regenerative braking requires a reliable bidirectional power conversion system capable of managing energy flow between the motor and the battery under varying operating conditions [6].

Bidirectional DC–DC converters play a crucial role in EV powertrains by enabling energy transfer in both directions—boost mode for propulsion and buck mode for battery charging [7]. High-gain bidirectional DC–DC converters (HGBDCs) are particularly important when there is a large difference between battery voltage and DC bus voltage [8]. These converters must meet several performance requirements, including high efficiency, fast dynamic response, low ripple, and robust operation under nonlinear conditions [9]. Despite advancements in converter topologies, challenges such as voltage stress, switching losses, and parameter variations persist, making the design of an effective control strategy essential [10].

Traditionally, Proportional–Integral–Derivative (PID) controllers have been widely used in power electronic applications due to their simple structure and ease of implementation [11]. While PID controllers provide satisfactory steady-state performance, they often struggle with nonlinear systems and rapid transient conditions commonly encountered in EV applications [12]. To address these limitations, intelligent control techniques such as Artificial Neural Networks (ANNs) have been introduced. ANN controllers can learn system behavior and adapt to changing conditions, offering improved transient performance and flexibility [13]. However, ANN-based methods require extensive training data and computational resources, which may limit their real-time applicability in EV systems [14].

Sliding Mode Control (SMC) has emerged as a robust alternative for controlling nonlinear systems with uncertainties. It offers fast dynamic response, strong disturbance rejection, and improved stability across a wide range of operating conditions [15]. In the context of high-gain bidirectional DC–DC converters, SMC ensures accurate voltage regulation and efficient energy transfer during both motoring and regenerative braking modes. Compared to PID and ANN controllers, SMC demonstrates superior performance in handling system nonlinearities and parameter variations. Therefore, this work focuses on a comprehensive analysis and comparison of PID, ANN, and SMC control strategies applied to HGBDCs in EV applications, aiming to identify the most effective approach for enhancing overall system performance.

LITERATURE SURVEY

The rapid advancement of electric vehicle (EV) technology has led to extensive research on power electronic converters and control strategies to improve efficiency and reliability. Early studies emphasized the importance of efficient energy management between the battery and motor drive, highlighting the role of bidirectional DC–DC converters in enabling both propulsion and regenerative braking operations [1]. Researchers have explored various converter topologies to achieve high voltage gain and improved efficiency, especially in applications where battery voltage levels differ significantly from the DC bus requirements [2]. High-gain converter structures such as isolated and non-isolated configurations have been proposed to enhance performance, but they often introduce challenges related to switching losses, voltage stress, and system complexity [3]. These studies underline the necessity of combining advanced converter designs with effective control techniques to ensure stable operation under varying load and driving conditions [4].

Several works have focused on improving converter performance through innovative circuit designs. Switched-capacitor and coupled-inductor-based converters have been introduced to achieve higher voltage gain without excessive duty cycles or component stress [5]. These designs offer advantages such as improved power density and reduced electromagnetic interference, making them suitable for EV applications [6]. Additionally, research on switching strategies has demonstrated that optimized switching sequences can significantly enhance converter efficiency and transient response [7]. However, despite these hardware improvements, it has been consistently observed that the overall performance of the system heavily depends on the control strategy employed. Conventional controllers often fail to maintain stability during rapid transitions between operating modes, indicating the need for more advanced and adaptive control methods [8].

Control strategies for bidirectional DC–DC converters have been widely investigated, with Proportional–Integral–Derivative (PID) controllers being the most commonly used due to their simplicity and ease of implementation [9].

PID controllers provide satisfactory steady-state performance and are widely adopted in industrial applications. However, their limitations become evident in nonlinear systems such as EV powertrains, where sudden load variations and dynamic operating conditions are frequent [10]. To overcome these limitations, Artificial Neural Network (ANN) controllers have been proposed, offering the ability to learn system behavior and adapt to changing conditions [11]. ANN-based approaches have shown improved transient response and reduced overshoot compared to PID controllers [12]. Nevertheless, their performance depends heavily on training data quality, and they often require high computational resources, which can be a constraint for real-time applications [13].

In recent years, Sliding Mode Control (SMC) has gained significant attention as a robust control technique for nonlinear systems. Studies have demonstrated that SMC provides excellent disturbance rejection, fast convergence, and strong robustness against parameter variations [14]. It has been successfully applied to various DC–DC converter topologies, showing superior performance compared to both PID and ANN controllers under dynamic conditions. Furthermore, hybrid approaches such as Neural Sliding Mode Control have been proposed to combine the adaptability of ANN with the robustness of SMC, resulting in improved overall performance [15]. Despite these advancements, there remains a need for comprehensive comparative studies that evaluate PID, ANN, and SMC controllers within a unified framework for high-gain bidirectional DC–DC converters in EV applications, which motivates the present research.

METHODOLOGY

The methodology begins with the identification of the system requirements for an electric vehicle (EV) powertrain, focusing on efficient bidirectional energy transfer between the battery and the motor. A high-gain bidirectional DC–DC converter (HGBDC) is selected as the core interface due to its capability to operate in both boost and buck modes. The converter is designed to meet the required voltage gain, efficiency, and dynamic performance under varying operating conditions. Key parameters such as input voltage, output voltage, switching frequency, duty cycle, and load specifications are defined based on the EV application. The converter topology is then modeled using appropriate circuit components, including inductors, capacitors, power switches, and diodes, ensuring minimal losses and high efficiency.

Following the system design, the mathematical modeling of the converter is carried out to understand its dynamic behavior. The operation of the converter is analyzed in both boost mode, where energy flows from the battery to the motor, and buck mode, where energy is transferred from the motor back to the battery during regenerative braking. State-space equations are derived to represent the system dynamics, considering parameters such as inductor current, capacitor voltage, and switching states. These equations are essential for designing control strategies and evaluating system stability under different operating conditions. The model is then implemented in a simulation environment to verify its correctness and observe the behavior of the converter.

Once the system model is established, control strategies are developed to regulate the output voltage and motor speed. Initially, a conventional PID controller is designed by tuning proportional, integral, and derivative gains to achieve acceptable steady-state performance. The controller processes the error between the reference speed and actual motor speed to generate control signals for pulse-width modulation (PWM). Next, an Artificial Neural Network (ANN) controller is implemented to enhance adaptability and performance under nonlinear conditions. The ANN is trained using input-output data obtained from the system, allowing it to learn the relationship between system states and control actions. The trained network is then integrated into the control loop to generate appropriate switching signals.

To further improve system robustness, a Sliding Mode Control (SMC) strategy is developed. A suitable sliding surface is defined based on system error dynamics, and a control law is formulated to drive the system states toward this surface. The SMC controller ensures fast convergence and strong disturbance rejection, making it highly suitable for EV applications with varying load conditions. To reduce chattering effects commonly associated with SMC,

smoothing techniques or boundary layer methods are incorporated. The controller output is used to generate PWM signals for controlling the converter switches, ensuring stable and efficient operation.

The complete system, including the HGBDC, battery model, and DC motor load, is implemented in MATLAB/Simulink for simulation analysis. The converter operates in continuous conduction mode to ensure smooth current flow and reduced ripple. The simulation is conducted for different scenarios, including forward motoring and regenerative braking, to evaluate the performance of each control strategy. Key performance parameters such as output voltage, inductor current, motor speed, torque, and battery state of charge are monitored and recorded. Transient conditions such as sudden speed changes and mode transitions are also analyzed to assess the dynamic response of the system.

Finally, a comparative analysis is performed to evaluate the effectiveness of PID, ANN, and SMC controllers. Performance metrics such as settling time, overshoot, steady-state error, and stability are used for comparison. The results are presented in the form of graphs and tables to provide a clear understanding of the differences between the control techniques. Based on the analysis, conclusions are drawn regarding the suitability of each controller for EV applications. The methodology ensures a systematic approach to designing, modeling, controlling, and evaluating the HGBDC system, ultimately identifying the most efficient and robust control strategy for improved EV performance.

PROPOSED SYSTEM

The proposed system focuses on the design and implementation of a high-gain bidirectional DC–DC converter (HGBDC) integrated with advanced control strategies for electric vehicle (EV) applications. The primary objective of the system is to ensure efficient energy transfer between the battery and the DC motor under both motoring and regenerative braking conditions. The converter is designed with multiple active switches, inductors, a diode, and a high-voltage side capacitor to achieve a high voltage gain while maintaining reduced switching stress and improved efficiency. This configuration enables the converter to operate in both boost mode, where energy flows from the battery to the motor, and buck mode, where energy is transferred from the motor back to the battery during braking. The bidirectional capability of the converter plays a crucial role in enhancing overall energy utilization and extending the driving range of the EV.

The working principle of the proposed HGBDC is based on controlled switching operations that regulate the flow of energy between the low-voltage battery side and the high-voltage DC bus. In boost mode, the switches are operated using pulse-width modulation (PWM) to increase the input voltage to the required level for driving the motor. The inductors store energy when the switches are turned on and release it to the output when the switches are turned off, thereby achieving voltage amplification. In buck mode, the converter operates in reverse, reducing the high DC bus voltage and transferring energy back to the battery. This operation is particularly important during regenerative braking, where the motor acts as a generator and feeds energy back into the battery. The smooth transition between these modes is essential for maintaining system stability and ensuring efficient operation under varying driving conditions.

To enhance the performance of the proposed system, three different control strategies are implemented and analyzed: PID, Artificial Neural Network (ANN), and Sliding Mode Control (SMC). The PID controller is used as a baseline due to its simplicity and ease of implementation, providing acceptable steady-state performance. However, to address the nonlinear characteristics of the converter and improve dynamic response, an ANN controller is introduced. The ANN controller is capable of learning system behavior and adapting to varying operating conditions, thereby reducing overshoot and improving transient performance. Furthermore, a Sliding Mode Controller is designed to provide robust control under system uncertainties and disturbances. The SMC ensures fast convergence, high stability, and strong disturbance rejection, making it highly suitable for EV applications where operating conditions frequently change.

The proposed system is modeled and simulated using MATLAB/Simulink to evaluate its performance under different operating scenarios. A lithium-ion battery is used as the energy source, and a DC motor is employed as the load to

represent the EV drivetrain. The system is tested under forward motoring and regenerative braking conditions, as well as during sudden changes in speed and load. Performance parameters such as output voltage, motor speed, torque, inductor current, and battery state of charge are analyzed for each control strategy. The simulation results demonstrate that the proposed HGBDC, when combined with advanced control techniques, significantly improves system efficiency, stability, and dynamic response. Among the controllers, the Sliding Mode Control approach exhibits superior performance in terms of reduced overshoot, faster settling time, and enhanced robustness, making it the most effective solution for modern EV powertrain applications.

RESULTS AND DISCUSSION

The simulation results of the high-gain bidirectional DC–DC converter (HGBDC) are analyzed to evaluate the performance of the existing system using the PID controller and the proposed system employing ANN and Sliding Mode Control (SMC) techniques. The system is modeled in MATLAB/Simulink and tested under both forward motoring (boost mode) and regenerative braking (buck mode) conditions. In the existing system, the PID controller regulates the output voltage and motor speed by minimizing the error between the reference and actual values. The results indicate that the converter successfully performs bidirectional energy transfer; however, the dynamic response is moderate, and the system exhibits noticeable overshoot and longer settling time during transient conditions. These limitations are more evident when the system is subjected to sudden speed changes or transitions between operating modes.

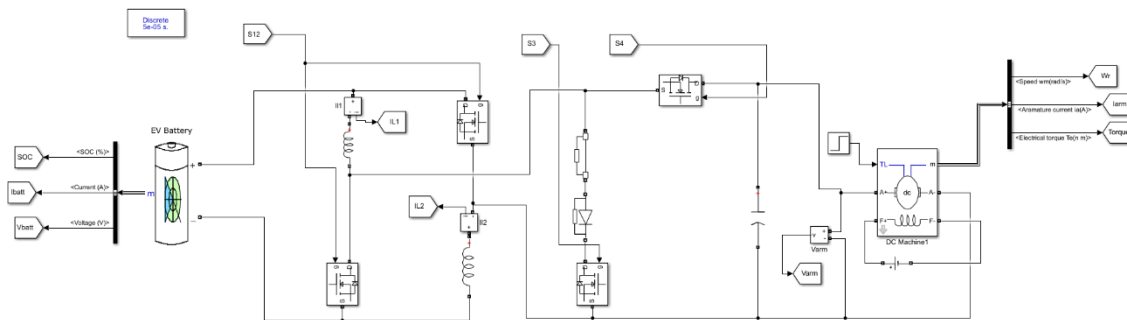


Fig 1. MATLAB/SIMULINK circuit diagram of HGBDC connected to battery source and a dc motor load

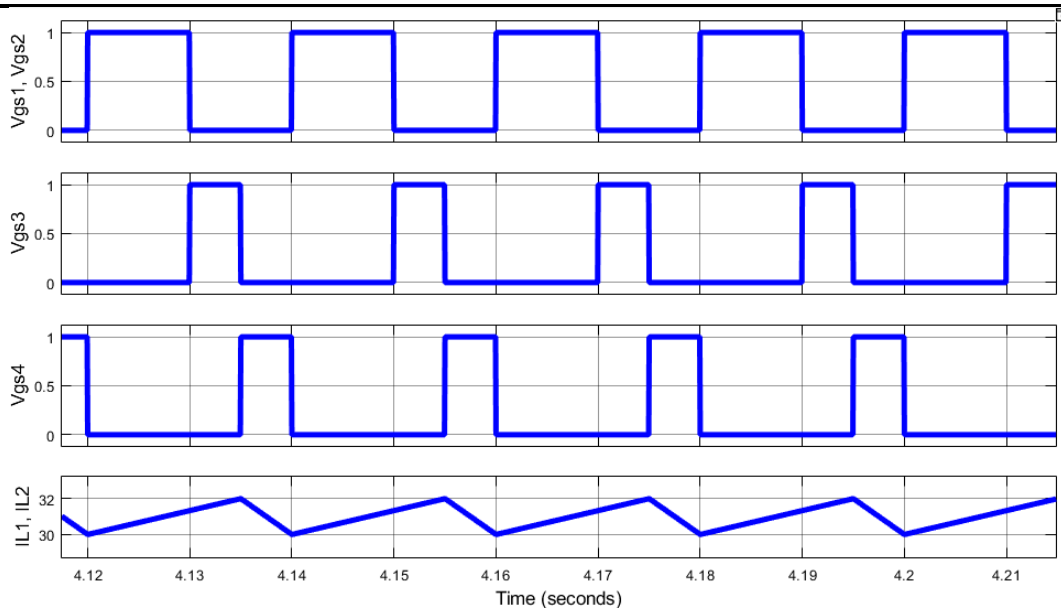


Fig 2. Switching signals for S1, S2, S3, S4 and inductor currents in boost mode of operation

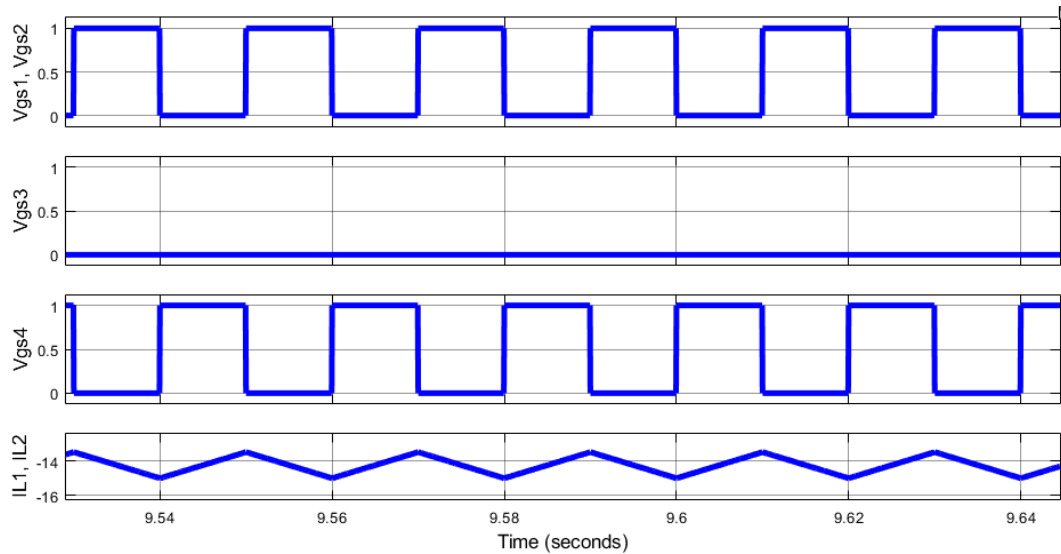


Fig3. Switching signals for S1, S2, S3, S4 and inductor currents in boost mode of operation.

During forward motoring operation, the converter operates in boost mode, stepping up the battery voltage to drive the DC motor at the desired speed. With the PID controller, the motor achieves the reference speed of 1750 rpm, but the response shows oscillations before reaching steady state. The inductor current stabilizes around the expected value, but fluctuations are observed during switching transitions. When the system transitions from motoring to regenerative braking, the PID controller struggles to maintain smooth operation. The motor speed decreases to 1150 rpm, and the current reverses direction, indicating successful energy flow back to the battery. However, the transition is not smooth, as there are spikes in torque and current, which may affect system reliability and efficiency in practical EV applications.

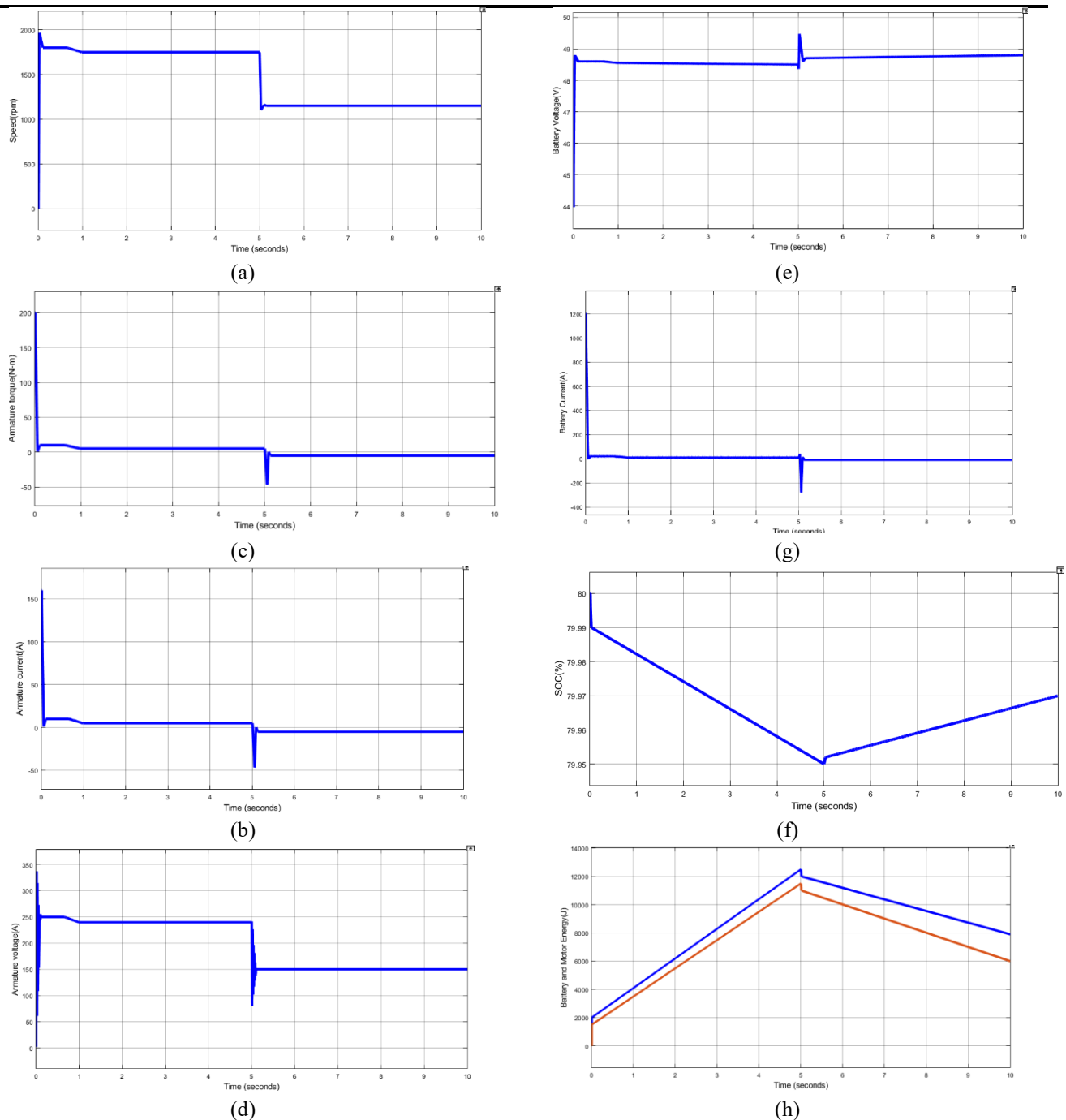
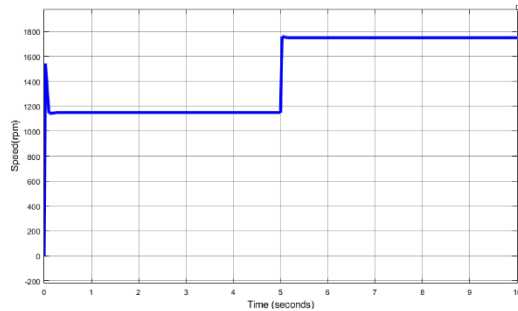


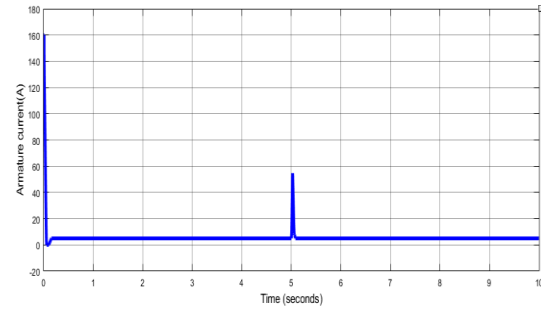
Fig 4. Simulation results for case1- transition of the motor from forward motoring to regenerative braking: (a) speed, (b) armature current, (c) armature torque, (d) armature (output) voltage of the motor, (e) battery voltage and (f) battery SoC (g) battery current (h) battery and motor energy.

To overcome these limitations, the proposed system incorporates an Artificial Neural Network (ANN) controller. The ANN controller improves the dynamic performance by learning the nonlinear characteristics of the system. Simulation results show that the ANN-based system achieves faster response and reduced overshoot compared to the PID controller. During forward motoring, the motor reaches the reference speed more quickly, and the oscillations are

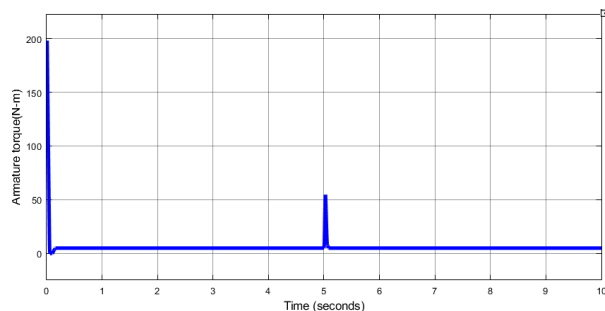
significantly minimized. Similarly, during regenerative braking, the ANN controller ensures a smoother transition with reduced current and torque fluctuations. However, despite these improvements, the ANN controller requires proper training and tuning, and its performance depends on the quality of the training data. Additionally, the computational complexity of ANN may pose challenges for real-time implementation in EV systems.



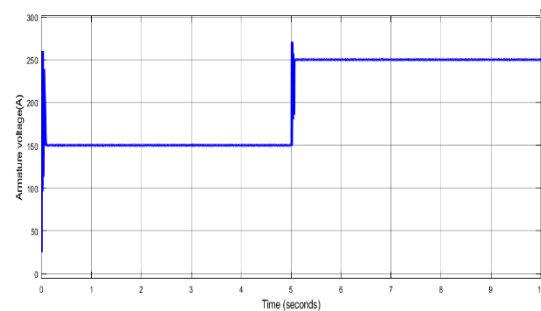
(a)



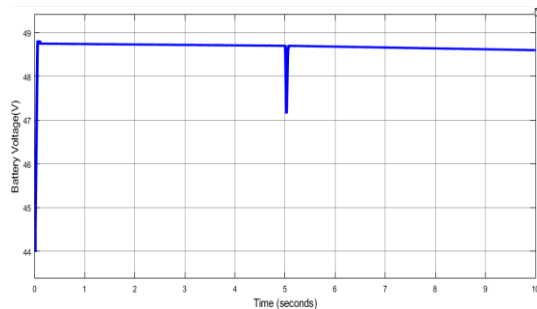
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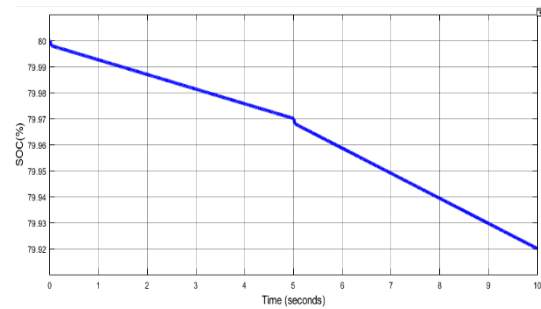
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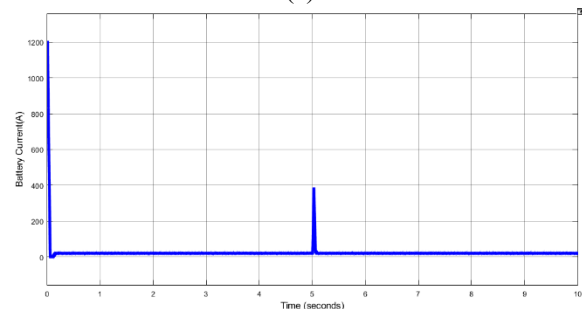
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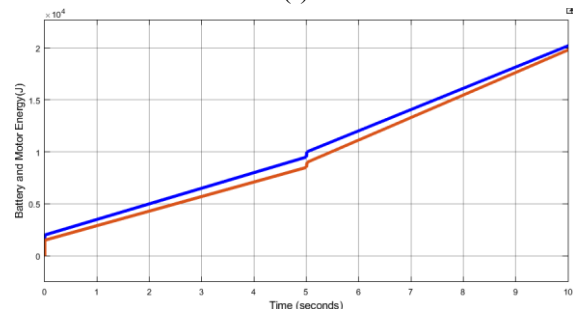
(e)



(f)



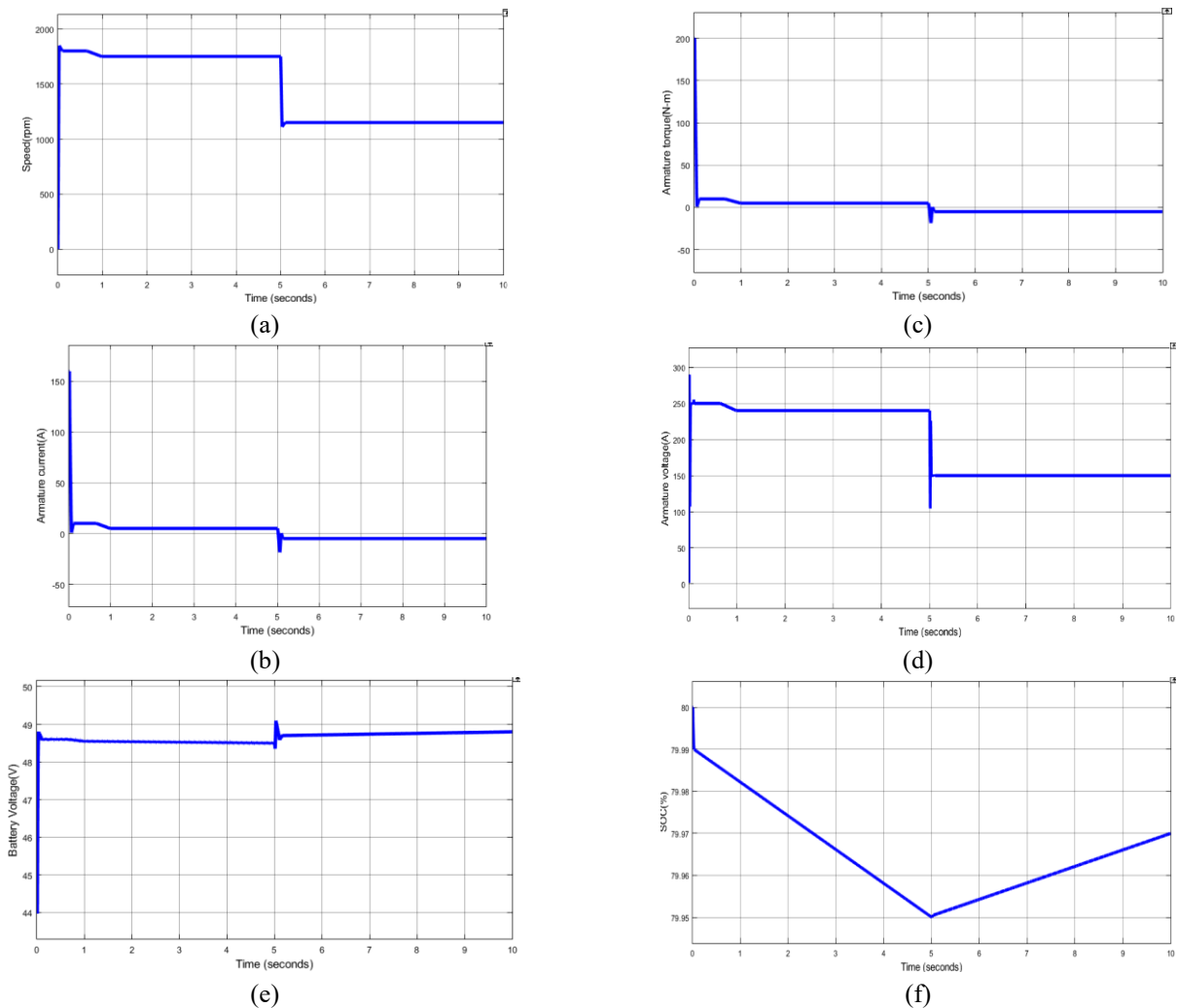
(g)



(h)

Fig 5. Simulation results for case 2- step change in speed during forward motoring: (a) speed, (b) armature current, (c) armature torque, (d) armature voltage, (e) battery SoC, (f) battery voltage, (g) battery current (h) battery and motor energy

The Sliding Mode Control (SMC) technique in the proposed system demonstrates superior performance compared to both PID and ANN controllers. The SMC-based system exhibits fast dynamic response, minimal overshoot, and excellent stability under varying operating conditions. During boost mode, the motor quickly reaches the reference speed with negligible oscillations, and the output voltage remains highly stable. The inductor current shows smooth behavior with reduced ripple, indicating efficient energy transfer. In regenerative braking mode, the SMC controller ensures a seamless transition, with minimal disturbances in torque and current. The battery charging process is also more efficient due to stable current flow, which enhances overall system performance.



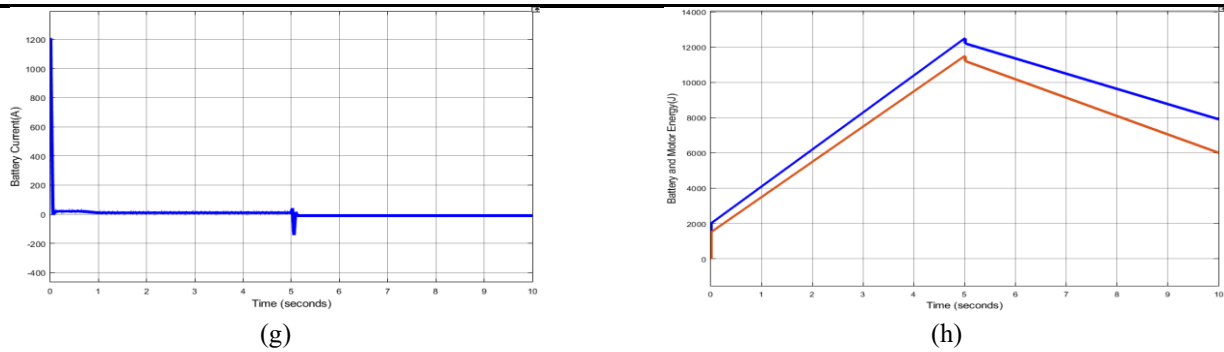
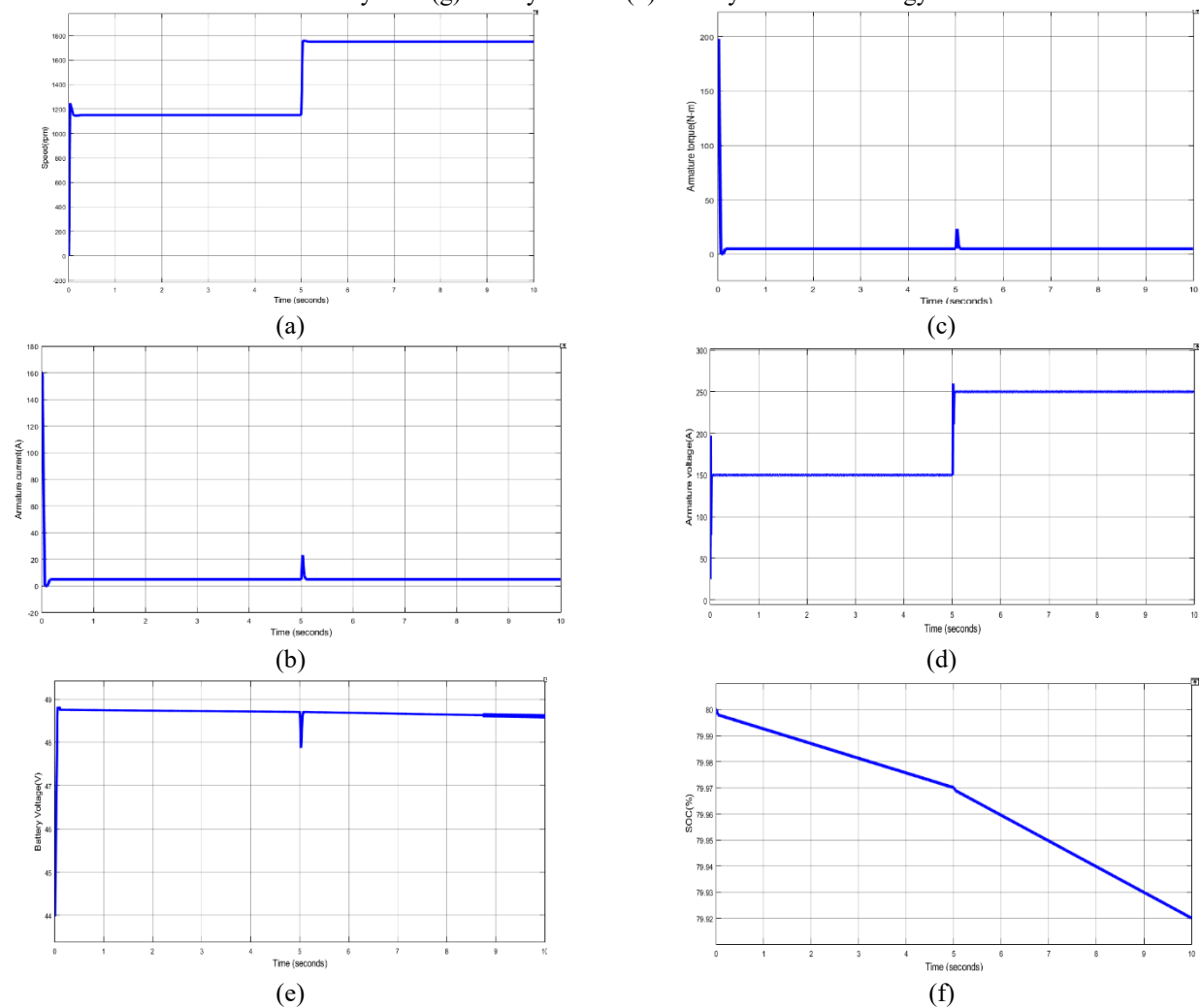


Fig 6. Simulation results for case1- transition of the motor from forward motoring to regenerative braking: (a) speed, (b) armature current, (c) armature torque, (d) armature (output) voltage of the motor, (e) battery voltage and (f) battery SoC (g) battery current (h) battery and motor energy



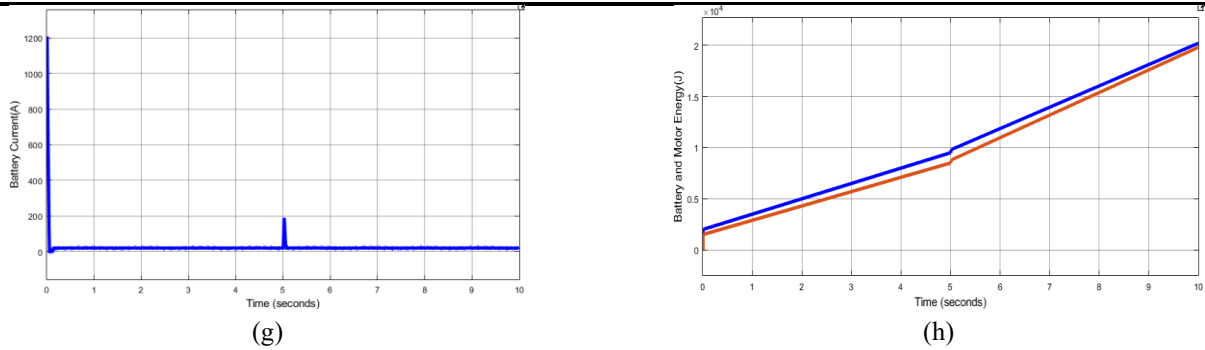
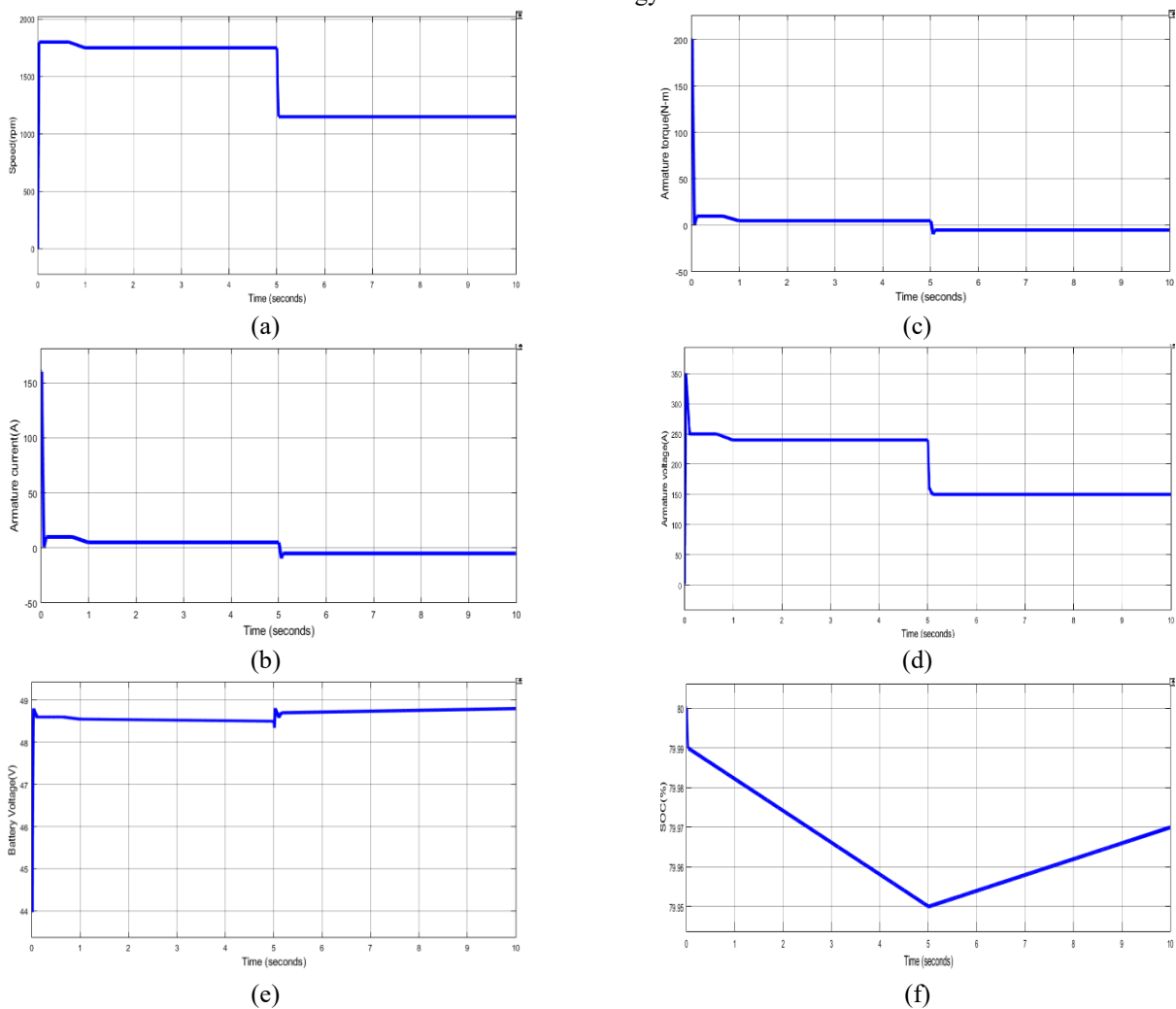


Fig 7. Simulation results for case 2- step change in speed during forward motoring: (a) speed, (b) armature current, (c) armature torque, (d) armature voltage, (e) battery SoC, (f) battery voltage, (g) battery current (h) battery and motor energy



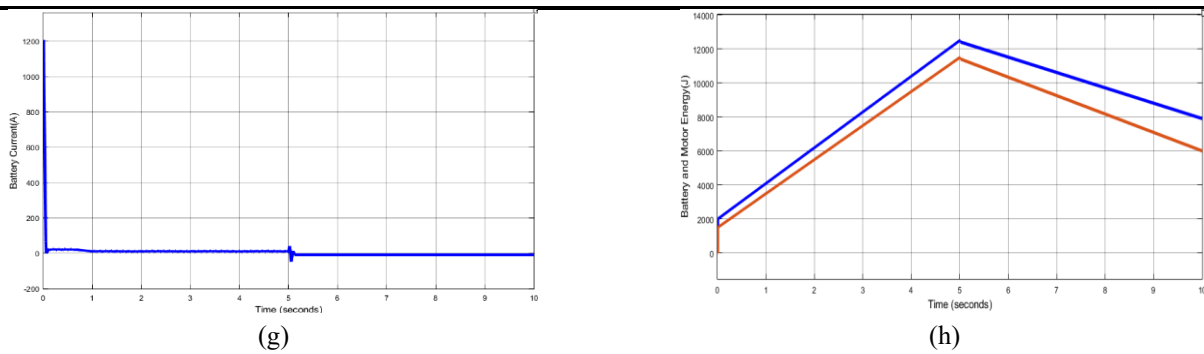
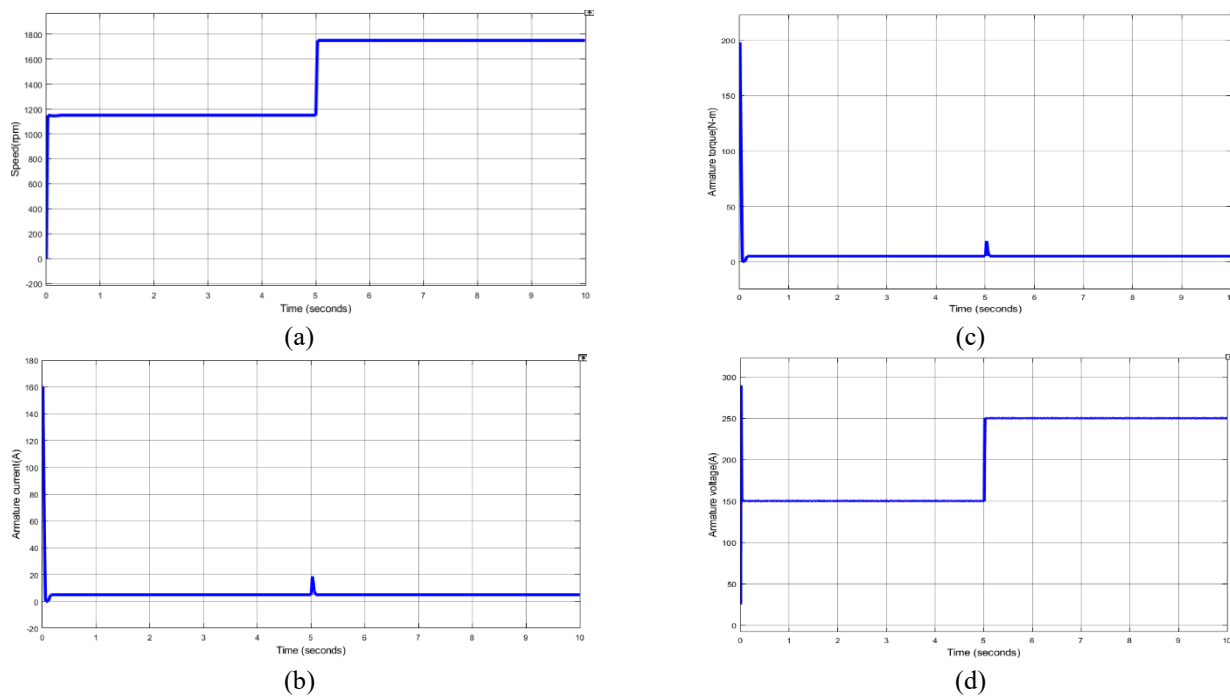


Fig 8. Simulation results for case1- transition of the motor from forward motoring to regenerative braking: (a) speed, (b) armature current, (c) armature torque, (d) armature (output) voltage of the motor, (e) battery voltage and (f) battery SoC (g) battery current (h) battery and motor energy

A comparative analysis of the three control strategies highlights the advantages of the proposed system. The PID controller, although simple and easy to implement, is less effective in handling nonlinearities and rapid transients. The ANN controller improves adaptability and transient response but introduces complexity and dependency on training. In contrast, the SMC controller provides a robust solution with superior performance across all operating conditions. Key performance metrics such as settling time, overshoot, steady-state error, and stability clearly favor the SMC approach. The reduction in oscillations and faster convergence make it highly suitable for EV applications, where reliability and efficiency are critical.



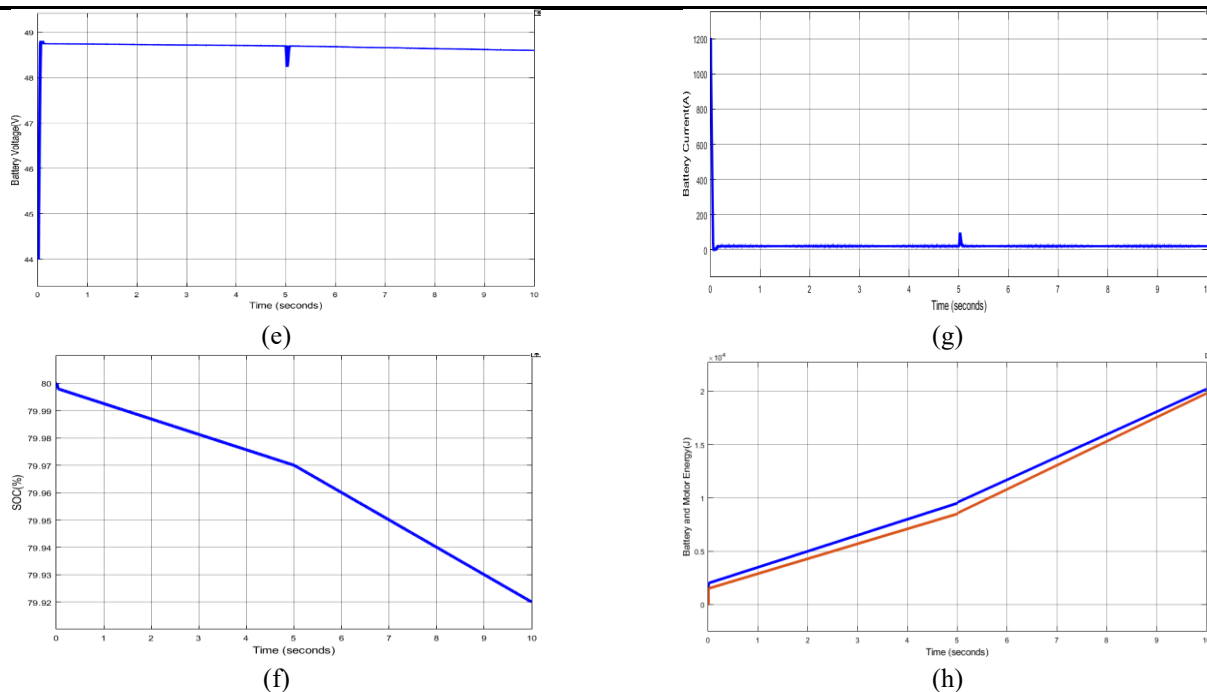


Fig 9. Simulation results for case 2- step change in speed during forward motoring: (a) speed, (b) armature current, (c) armature torque, (d) armature voltage, (e) battery SoC, (f) battery voltage, (g) battery current (h) battery and motor energy

Overall, the simulation results confirm that the proposed system with advanced control strategies significantly enhances the performance of the HGBDC in EV applications. The ability to maintain stable operation during both motoring and regenerative braking conditions ensures efficient energy utilization and improved driving range. Among the controllers, Sliding Mode Control emerges as the most effective technique, offering the best balance between robustness, speed, and stability. These findings validate the suitability of the proposed system for modern electric vehicle powertrains and highlight the importance of advanced control methods in achieving optimal performance.

CONCLUSION

This work presented the design, modeling, and performance evaluation of a high-gain bidirectional DC–DC converter (HGBDC) for electric vehicle applications, with a focus on improving energy transfer efficiency and dynamic response under varying operating conditions. The system was analyzed using three different control strategies: PID, Artificial Neural Network (ANN), and Sliding Mode Control (SMC). The existing PID controller demonstrated simple implementation and acceptable steady-state performance but showed limitations in handling nonlinearities, rapid transients, and mode transitions between motoring and regenerative braking. The ANN controller improved adaptability and transient response by learning system behavior; however, it introduced increased computational complexity and dependence on training data. In contrast, the proposed SMC technique exhibited superior robustness, faster convergence, minimal overshoot, and enhanced stability under all tested conditions. Simulation results confirmed that SMC provides efficient and smooth bidirectional energy transfer with improved voltage regulation and reduced oscillations. Therefore, the study concludes that Sliding Mode Control is the most effective control strategy for HGBDC in EV powertrains, offering a reliable and high-performance solution for modern electric vehicle energy management systems.

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