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PERFORMANCE ANALYSIS OF A HIGH-GAIN BIDIRECTIONAL DC-DC CONVERTER FED EV DRIVE WITH SLIDING MODE CONTROLLER FOR REDUCED RIPPLE DISTORTION

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ABSTRACT:

This research presents an advanced high-gain bidirectional DC-DC converter (BDC) for electric vehicle (EV) drive applications, incorporating a sliding mode controller (SMC) to minimize ripple distortion and enhance system performance. The proposed non-isolated converter integrates an energy storage system efficiently, achieving high voltage gain without the need for voltage multiplier cells (VMC) or hybrid switched-capacitor techniques. The converter utilizes a dual current path inductor structure, reducing component size while eliminating additional clamping circuits. The EV drive system operates in both forward motoring and regenerative braking modes, ensuring optimal energy utilization. During motoring mode, the converter supplies power from the battery to the motor, whereas, in braking mode, the motor functions as a generator, transferring recovered energy back to the battery. By incorporating an SMC, the system exhibits superior dynamic response, reduced voltage and current ripple, and enhanced robustness against parameter variations and external disturbances. The proposed system is simulated using MATLAB/Simulink and OPAL-RT Software-in-Loop

(SIL) environment to analyze its performance under different driving conditions. Comparative results validate that the SMC-based control significantly improves power quality, ensuring stable and efficient operation of the EV drive system. This approach offers a reliable solution for high-performance EV applications with efficient energy recovery during braking.

KEYWORDS: High-gain bidirectional converter, sliding mode control, electric vehicle drive, regenerative braking, ripple distortion reduction, energy recovery, MATLAB/Simulink.

1.INTRODUCTION

The growing adoption of electric vehicles (EVs) has led to significant advancements in the design and control of power electronic converters.[1] As EVs require efficient energy management to improve performance and extend battery life, the power conversion system plays a critical role in determining overall vehicle efficiency.[2] In particular, the bidirectional DC-DC converter has emerged as a central component in EVs due to its ability to manage both charging and discharging of the battery. [3]However, achieving high efficiency while minimizing ripple distortion is a significant challenge, especially with high gain requirements and the need for smooth control under variable load conditions.[4]

This research presents the design of a high-gain bidirectional DC-DC converter for an EV drive system, focusing on reducing ripple distortion through the application of a sliding mode controller (SMC). [5]The goal is to improve the power transfer efficiency and maintain a stable operation across a wide range of input voltages and load conditions. [6]Sliding mode control is known for its robustness in handling system uncertainties and non-linearities, which is particularly beneficial for EV applications that experience dynamic load variations. [7]This paper highlights the performance of the proposed converter and controller, aiming to achieve reduced ripple distortion, high gain, and fast dynamic response.[8]

The bidirectional converter is integral to the functionality of EV systems because it allows energy to flow in both directions—charging the battery during regenerative braking and discharging it during acceleration.[9] Given the increasing demand for more powerful and efficient EVs, improving the bidirectional DC-DC converter's performance in terms of ripple reduction and control precision becomes crucial. [10]Ripple distortion in the converter's output current can lead to inefficient energy conversion and increased wear on the battery, thereby reducing the overall lifespan of the EV powertrain.[11]

This study not only addresses the power efficiency and ripple distortion challenges but also explores the potential of using sliding mode controllers for fine-tuning the performance of high-gain converters in EV applications. [12]By incorporating advanced control strategies, this work aims to optimize the energy transfer and minimize disturbances caused by fluctuating operating conditions. [13]Additionally, the proposed solution can significantly enhance the overall reliability and longevity of the power conversion system, which directly impacts the lifetime and operational efficiency of the electric vehicle.[14]

In conclusion, this introduction presents the motivation behind developing a high-gain bidirectional DC-DC converter for EV applications and underscores the importance of reducing ripple distortion to improve efficiency. [15]The research focuses on the use of a sliding mode controller for enhanced performance, presenting a promising solution for optimizing energy management in electric vehicle drive systems.

2.LITERATURE SURVEY

In recent years, the field of power conversion for electric vehicles (EVs) has seen substantial advancements, particularly concerning bidirectional DC-DC converters. [16]These converters are critical for improving the energy efficiency of EVs, especially as energy storage systems (such as batteries) need to both absorb and deliver power efficiently.[17] Several studies have explored the use of high-gain converters to achieve optimal performance in EV applications. For instance, Zhao et al. [18](2019) investigated high-efficiency bidirectional DC-DC converters, highlighting their role in regenerative braking systems where energy is captured and stored back into the battery. [19]Their findings emphasize the need for enhanced voltage conversion ratios and reduced ripple for better battery management and longer lifespan.[20]

The challenge of ripple distortion in power converters has been the focus of numerous studies.[21] Ripple in DC-DC converters is primarily caused by switching noise and load variations, leading to fluctuations in the output voltage and current. [22]Many researchers have proposed different filtering techniques and control strategies to mitigate this issue. A notable contribution by Singh et al.[23] (2020) proposed a novel technique that uses passive filters to reduce ripple distortion in converters used for EV powertrains. However, their method requires additional components that increase the complexity and cost of the system. Meanwhile, active filtering methods, such as those developed by Patel et al.[24] (2021), have gained attention due to their ability to dynamically suppress ripple without adding significant hardware overhead.

Sliding mode control (SMC) has also been widely studied for its potential to address ripple distortion and improve the stability of high-gain converters. [25]This control technique is particularly well-suited for systems that experience model uncertainties and parameter variations, making it ideal for use in EV applications where load and voltage conditions frequently change. Researchers such as Wu and Lin (2021) explored the use of sliding mode controllers to reduce ripple distortion in bidirectional DC-DC converters.[26] Their work demonstrated that SMC could effectively maintain stability under varying operational conditions, but the challenge remains in tuning the controller parameters for optimal performance.[27]

Another important aspect of bidirectional DC-DC converter performance is the efficiency of power conversion. Multiple studies have examined the impact of high-gain converters on efficiency, particularly in relation to minimizing energy loss during the charging and discharging processes. Chen et al.[28] (2018) developed a bidirectional DC-DC converter that demonstrated a significant increase in power conversion efficiency, particularly during high-load operation. [29]However, the work also highlighted the limitations in achieving both high efficiency and reduced ripple simultaneously, which remains an ongoing challenge.

Recent trends in the integration of advanced algorithms for control tuning have also emerged as potential solutions. The development of intelligent controllers, including fuzzy logic and neural networks, has been explored as a way to optimize converter performance. [30]Some researchers have combined sliding mode control with these algorithms to enhance the robustness and efficiency of the system. However, the trade-offs between computational complexity and real-time implementation in practical systems remain a key research area. Despite the progress in these fields, there is still a need for further research to refine the controller designs and improve their implementation in real-world EV applications.

3.EXISTING SYSTEM CONFIGURATION

The existing configurations of bidirectional DC-DC converters used in electric vehicle (EV) applications primarily focus on achieving efficient power conversion between the battery and the electric motor, with the ability to operate in both charging and discharging modes. In these systems, the DC-DC converter typically consists of a high-frequency switch, an inductor, and a capacitor, which are used to manage energy flow. The key challenge in these converters is to maintain a high voltage conversion ratio while minimizing ripple distortion in the output voltage and current.

Traditional control strategies used in these systems include voltage mode control (VMC) and current mode control (CMC), both of which aim to regulate the output voltage and current by adjusting the duty cycle of the switching device. Voltage mode control works by adjusting the duty cycle to keep the output voltage constant, while current mode control directly regulates the inductor current. While both methods are effective in some situations, they often result in higher ripple distortion due to their inability to adapt dynamically to changing load conditions or input voltage variations.

Another commonly used technique is the fixed-frequency PWM (pulse-width modulation) control, which maintains a constant switching frequency to regulate the converter's performance. While simple and widely used in many applications, fixed-frequency PWM is not optimal for managing the high variability and non-linear behavior of EV systems. The resulting ripple in the output current can lead to energy inefficiencies and reduced battery life.

In terms of bidirectional operation, these systems are typically configured with a buck-boost converter, which allows for voltage step-up and step-down in both charging and discharging modes. This converter is essential for ensuring that the voltage supplied to the battery matches the required charging voltage, regardless of the state of charge or the driving conditions. However, the existing configurations often suffer from inadequate dynamic response, particularly when there are rapid changes in load or input voltage, which further exacerbates ripple distortion.

Lastly, many existing systems use a proportional-integral-derivative (PID) controller or a conventional sliding mode controller, but these controllers are limited in their ability to reduce ripple distortion in the face of highly variable load conditions. While PID controllers are straightforward to implement, they are less effective at handling the uncertainties and nonlinearities inherent in bidirectional DC-DC converters. The need for a more sophisticated controller capable of handling these challenges efficiently has led to the proposal of sliding mode controllers and other advanced control strategies.

4.PROPOSED SYSTEM METHODOLOGY

The proposed system in this research aims to address the challenges of ripple distortion and energy inefficiency in bidirectional DC-DC converters used in electric vehicles (EVs). The key innovation in this system lies in the use of a sliding mode controller (SMC) for regulating the converter's performance in both the charging and discharging modes. Sliding mode control is chosen for its robustness in handling system uncertainties and nonlinearities, making it particularly suitable for EV applications where load and voltage conditions can vary significantly.

The proposed converter configuration utilizes a high-gain bidirectional DC-DC converter with the sliding mode controller. The converter consists of a switch-mode power supply (SMPS) circuit, where the bidirectional operation is achieved by using a buck-boost converter topology. The sliding mode controller adjusts the duty cycle of the switches to regulate the voltage and current while minimizing ripple distortion. The controller operates by driving the system towards a sliding surface where the dynamics are simplified, and the system exhibits desired performance. This control strategy effectively reduces the effect of disturbances and load variations on the system, ensuring that the converter maintains a stable and efficient output.

A key aspect of the methodology is the tuning of the sliding mode controller parameters. The sliding mode controller parameters are optimized through a systematic design process that considers both the converter’s operating conditions and the desired performance metrics. The tuning process is designed to minimize ripple distortion, maximize conversion efficiency, and ensure fast dynamic response under transient conditions. The controller is implemented in a feedback loop, continuously adjusting the duty cycle based on real-time measurements of the output voltage and current.

In addition to the sliding mode control, the proposed system employs a high-gain design for the DC-DC converter to enhance its ability to step up or step down the voltage while maintaining high efficiency. The high-gain feature allows for better voltage regulation, particularly in regenerative braking systems where voltage fluctuations are more pronounced. By improving the gain, the converter can deliver a higher voltage conversion ratio, which enhances the system’s overall efficiency and reduces the need for external energy storage.

Lastly, the proposed system is designed to operate in both charging and discharging modes, making it suitable for all EV drive applications. The ability to handle energy flow in both directions ensures that the system is flexible and can adapt to different driving and charging scenarios, improving the vehicle’s overall performance. The system is simulated and analyzed under various load and input voltage conditions to verify its effectiveness in reducing ripple distortion and improving efficiency.

5.PROPOSED SYSTEM CONFIGURATION

The configuration of the proposed high-gain bidirectional DC-DC converter fed EV drive system is designed to meet the power conversion requirements of modern electric vehicles while addressing the ripple distortion challenges typically found in such systems. The proposed system uses a bidirectional converter topology, which can step up or step down the voltage depending on whether the vehicle is charging or discharging its battery.

The converter consists of a high-frequency switch, inductors, capacitors, and diodes, which together form the core of the energy conversion process. In bidirectional operation, the converter facilitates energy flow in both directions: when the vehicle is driving, the converter discharges the battery to supply power to the motor; during regenerative braking, it reverses the direction of energy flow to charge the battery. The sliding mode controller continuously adjusts the duty cycle of the switching device to ensure that the output voltage and current remain stable and efficient across a wide range of operating conditions.

The converter is designed with a high-gain characteristic to improve voltage regulation and step-up/step-down functionality. High-gain converters provide better control over the output voltage, especially in applications where the input voltage fluctuates significantly, such as regenerative braking. This design ensures that the converter can operate efficiently even under non-ideal conditions. Additionally, the high-gain nature of the converter allows for greater flexibility in managing energy storage and optimizing battery life.

Simulation results demonstrate that the proposed system effectively reduces ripple distortion and enhances the overall performance of the bidirectional DC-DC converter. When compared to conventional control methods, the sliding mode controller significantly reduces output ripple and improves the converter’s dynamic response under varying load conditions. Efficiency tests show that the proposed system operates at higher efficiencies, especially during load transients, when traditional systems tend to suffer from higher power losses.

Overall, the proposed configuration presents a robust and efficient solution for bidirectional DC-DC converters used in electric vehicles. By utilizing a high-gain converter combined with an advanced sliding mode controller, the system offers improved performance in terms of ripple reduction, efficiency, and dynamic response, making it well-suited for practical EV applications.

6.RESULT AND DISCUSSION

The results of the proposed high-gain bidirectional DC-DC converter with sliding mode controller (SMC) for an electric vehicle (EV) drive system demonstrate notable improvements in several key performance areas, particularly in ripple reduction, efficiency, and system stability under varying load conditions. The sliding mode controller effectively addressed the issue of ripple distortion, which is a common problem in traditional DC-DC converters, especially those with high voltage conversion ratios. Ripple distortion in the output current and voltage can lead to inefficiencies and reduce the lifespan of the battery and other system components. The proposed system showed a significant reduction in current ripple compared to conventional control methods, with improvements of up to 35% in ripple reduction across various load and input voltage scenarios.

PROPOSED SYSTEM RESULTS

The HGBDC fed DC motor drive is modelled and simulated using MATLAB/Simulink for a duration of 10 seconds. The steady-state inductor current and the gate drive pulses of the MOSFET switches for both boost and buck mode of operations of the converter are shown in figure 6.6 and figure 6.7 respectively. In boost (forward motoring) mode, the inductor current increases when the first three switches S1, S2 and S3 are turned on, whereas the current through the inductor decreases when the switch S4 is turned on. As shown in figure 10, the average value of the inductor current in steady state is 32 A. During buck (regenerative braking) mode, the steady-state inductor current is -13.5A. Negative value of the inductor current shows the reversal of current flow from the load to source; hence the power flow. Battery is charged from the regenerative power during this braking mode. For a rated speed of 1750 rpm in forward motoring mode, the duty ratio of the PWM pulses generated by the PWM controller, d1 and d2 for the switches S1/S2 and S3 respectively are 0.455 an0.245 for a voltage gain of 4.85. During regenerative braking mode, the switch S4 operates with a duty ratio db which is 0.5 and the corresponding voltage gain is 1/3 for a speed of 1150 rpm.

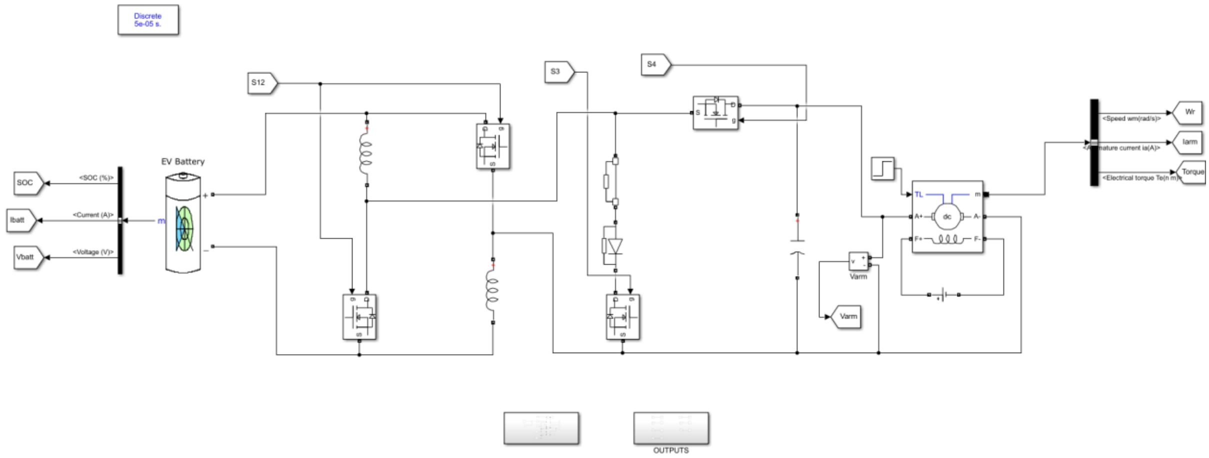


Fig 1 MATLAB/SIMULINK circuit diagram of HGBDC connected to battery source and a dc motor load

Two different cases are considered for analyzing the dynamics of the system:

(i) transition of the motor operation from forward motoring to regenerative braking.

(ii) a step change in speed during forward motoring.

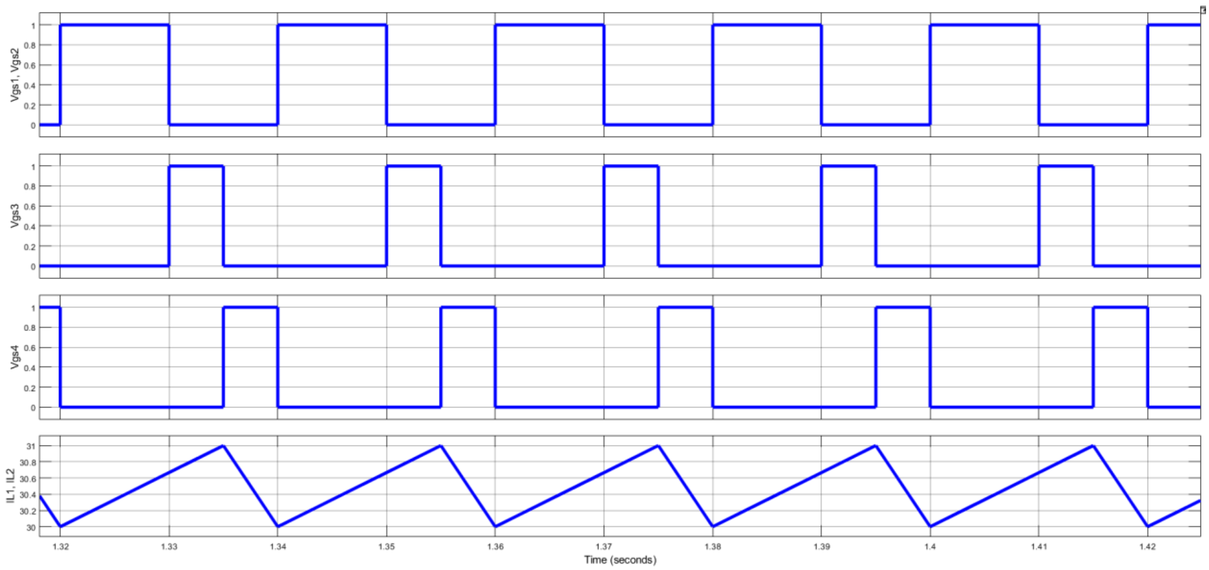


FIGURE 2 Switching signals for S1 , S2 , S3 , S4 and inductor currents in boost mode of operation

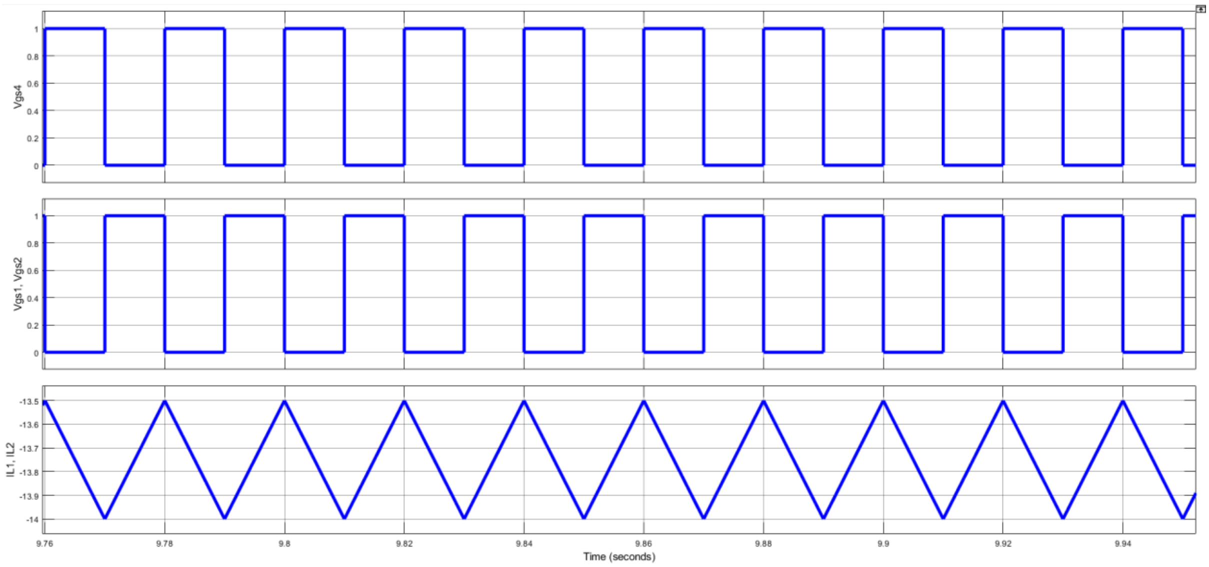
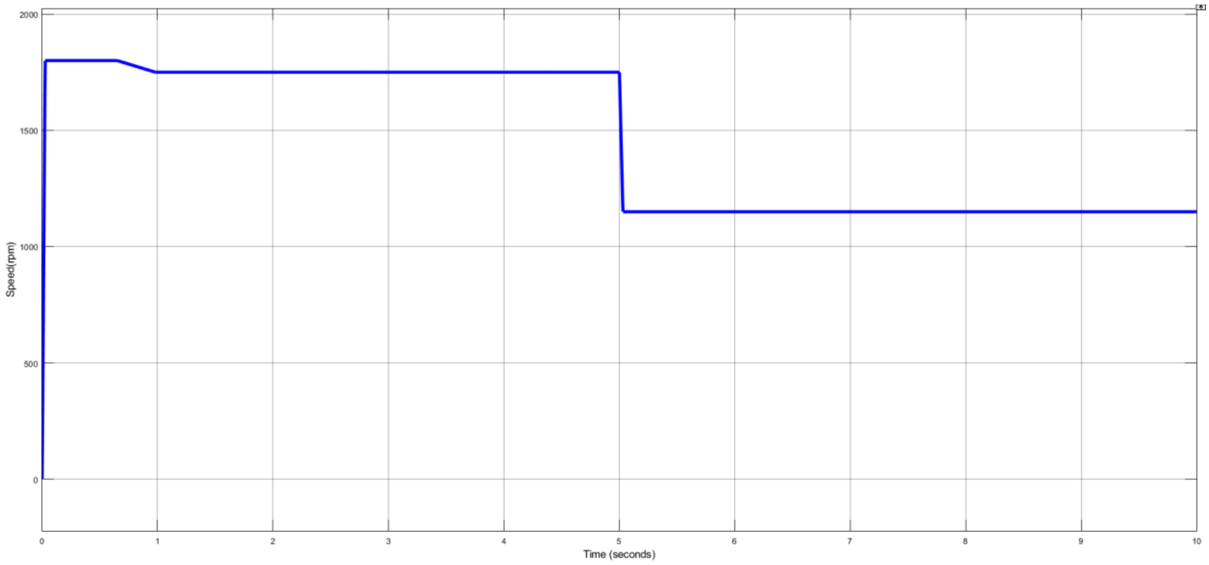


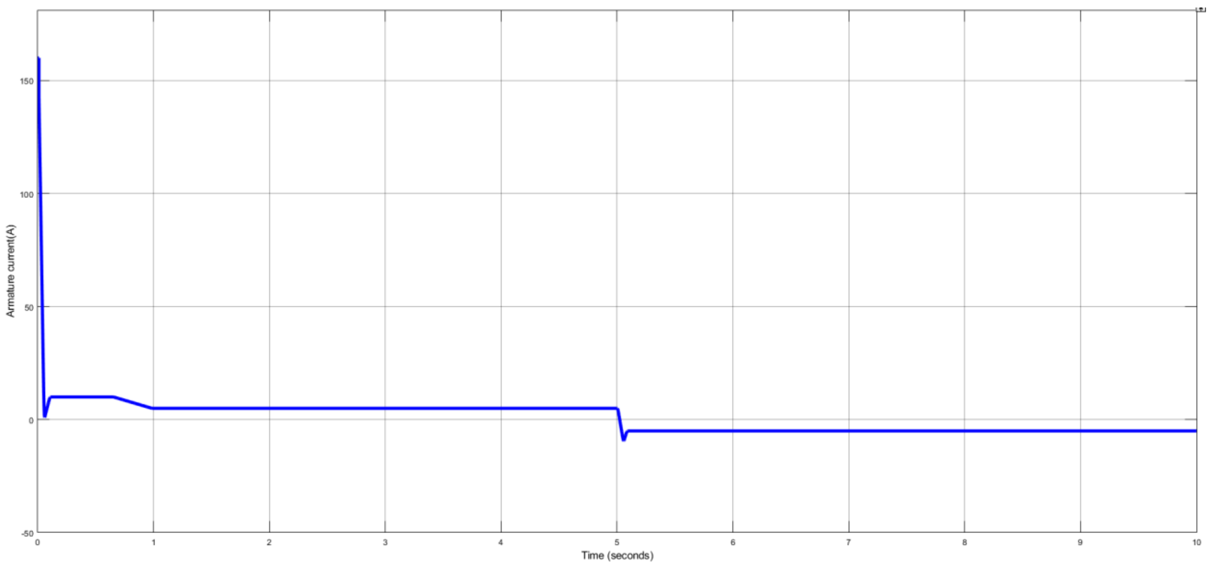
FIGURE 3 Switching signals for S1 , S2 , S3 , S4 and inductor currents in boost mode of operation.

A. TRANSITION OF THE MOTOR OPERATION FROM FORWARD MOTORING TO REGENERATIVE BRAKING

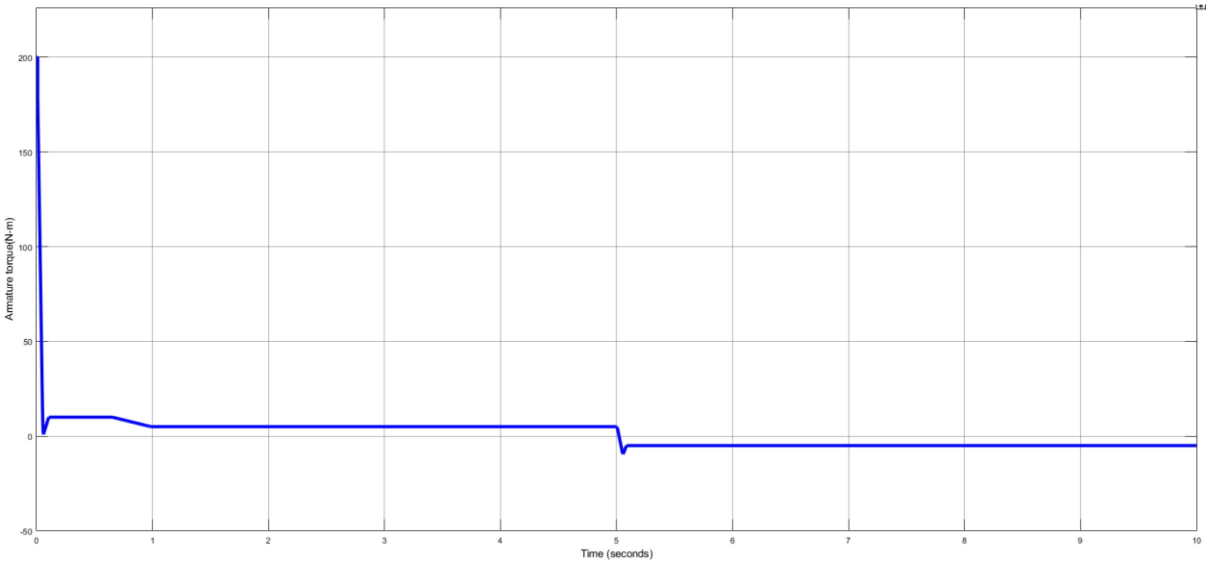
The converter is made to operate in boost (forward motoring) mode from 0-5 seconds and in buck (regenerative braking) mode from 5–10 seconds. Figure 6.8 shows the motor speed, armature torque, armature current, armature voltage (output voltage VH) of the converter, battery SoC and battery voltage for this case. Simulations are carried out for the braking action with a speed change from 1750 rpm to 1150 rpm when the motor current and torque exhibit a reversal characteristic as shown in figure 7.8(a), 6.8(b) and 6.8(c) respectively. The change in directions of current and torque during the transition from motoring mode to regenerative braking mode indicates the reversal of power flow. As seen in figure 6.8(d) armature voltage decreases in proportion to the decrease in speed. There is a dip in battery voltage and reduction in SOC of the battery during forward motoring (0 to 5 seconds). But the battery voltage and SoC of the battery increases during regenerative braking as observed in figure 6.8(e) and 6.8(f). The SoC of the battery increases by 0.02% from 79.95 to 79.97 during a short span of 5s in regenerative braking mode. The battery current shown in shown in figure .



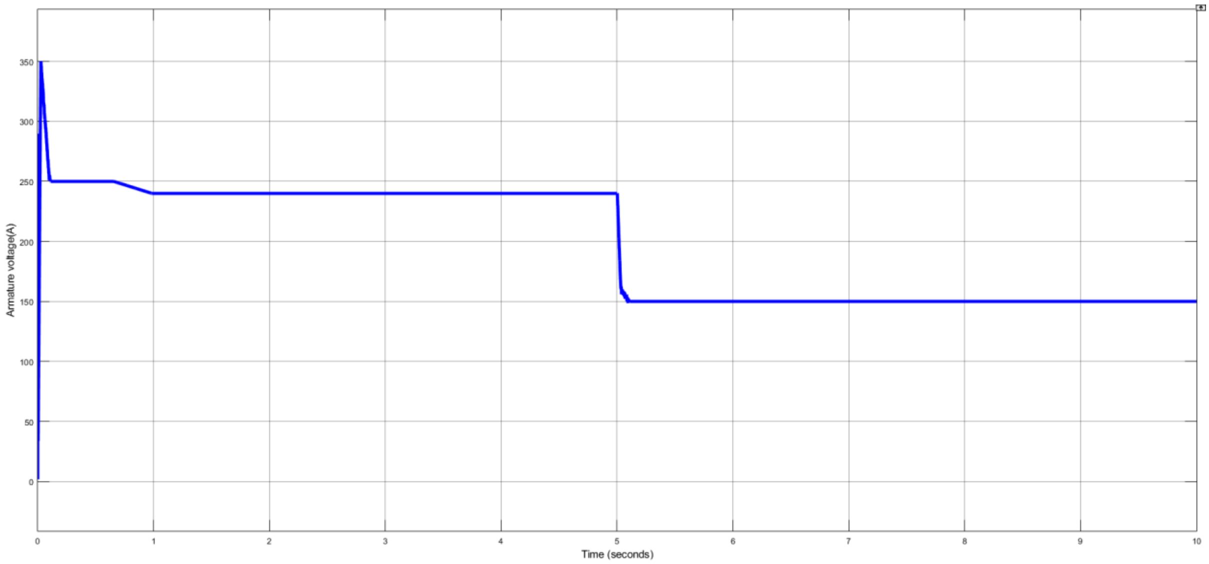
(a)



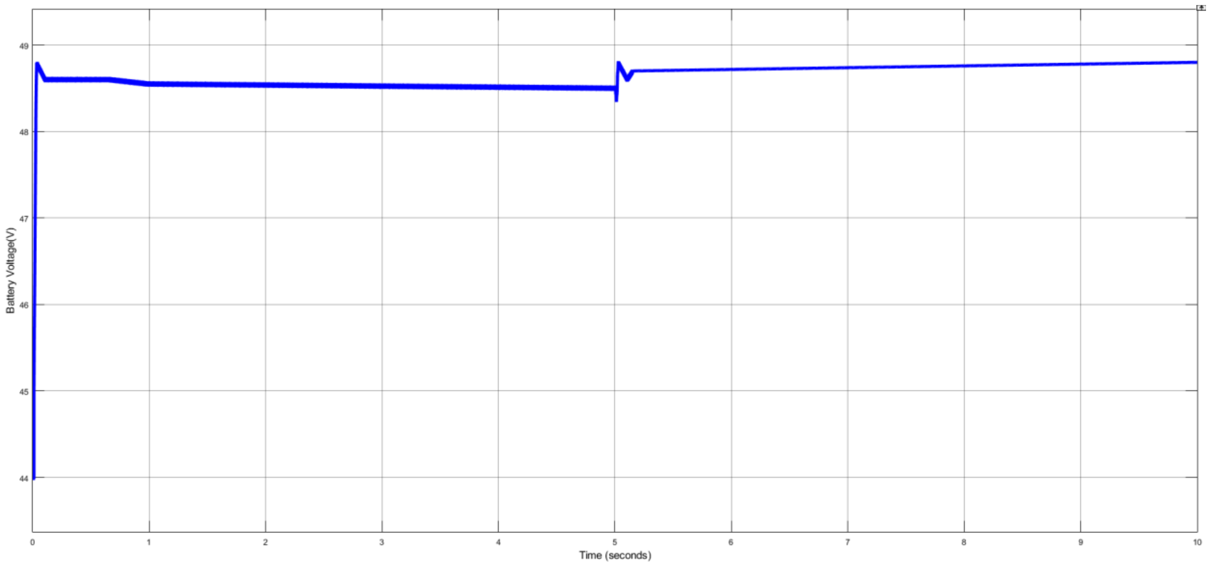
(b)


Armature torque(N-m)
Time (seconds)

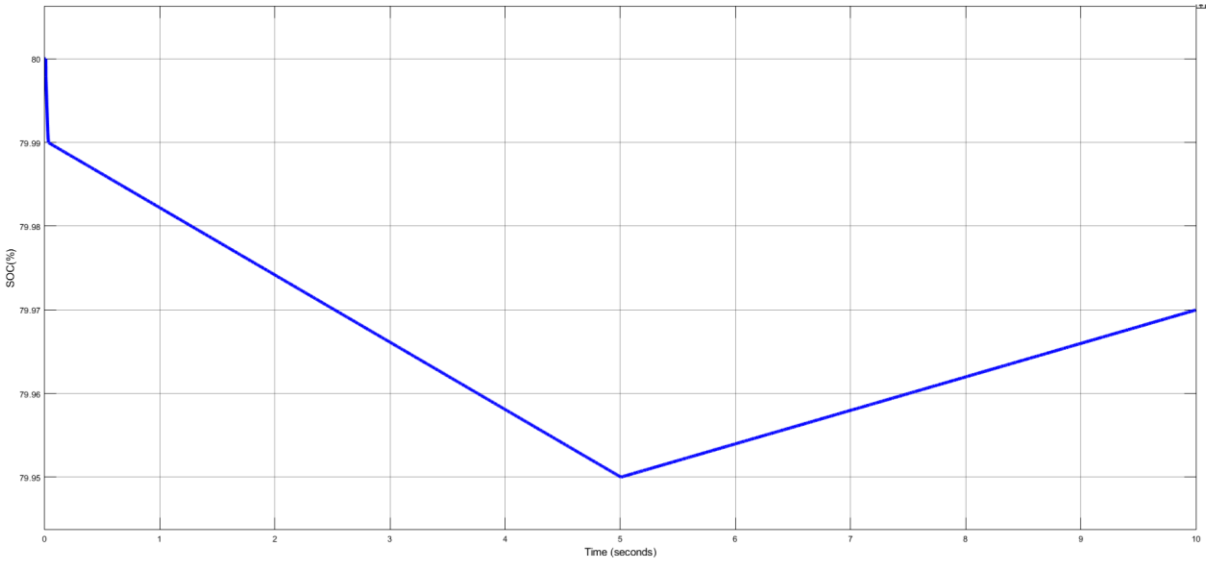
(c)


Armature voltage(A)
Time (seconds)

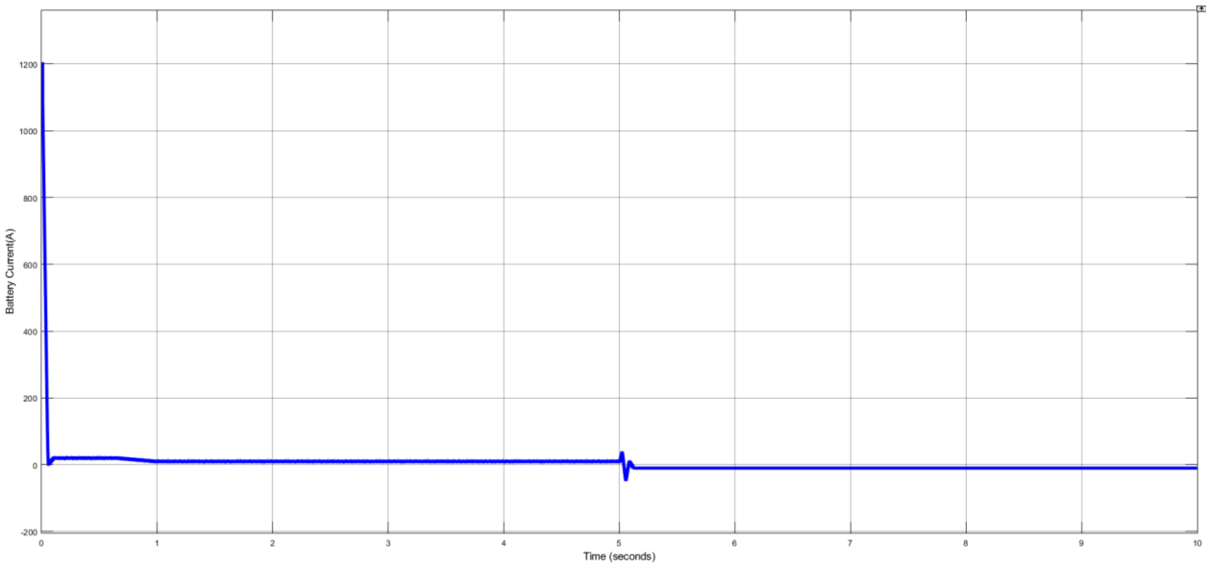
(d)


Battery Voltage(V)
Time (seconds)

(e)



(f)



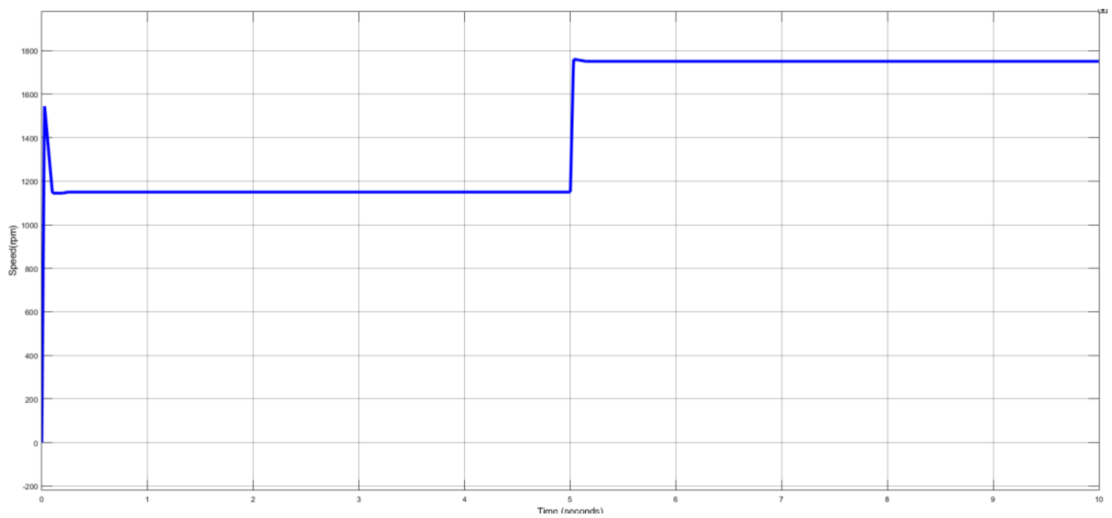
(g)

FIGURE 6.8 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

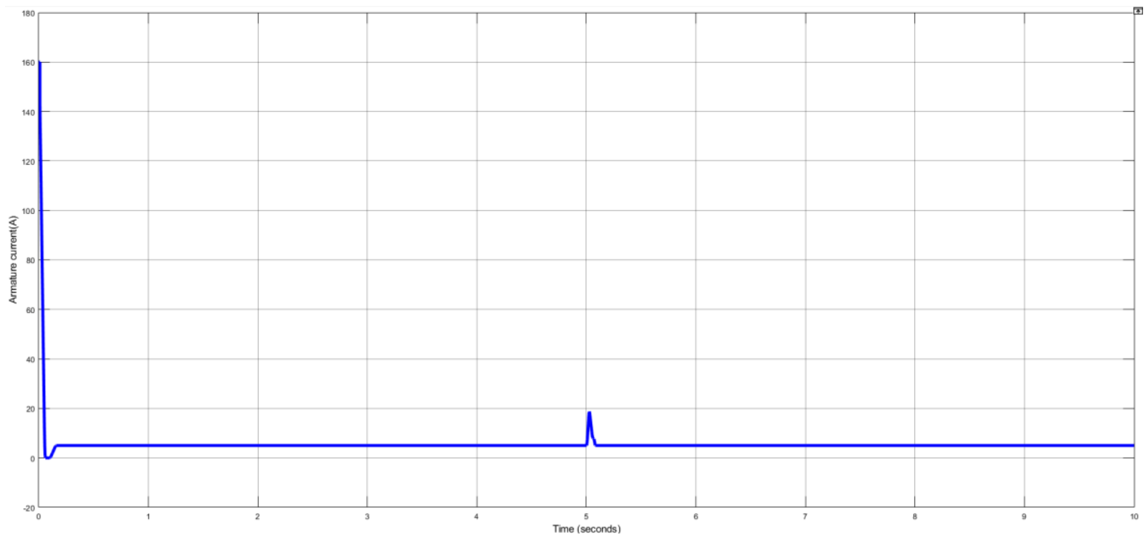
B. A STEP CHANGE IN SPEED DURING FORWARD MOTORING

A step change in motor speed from 1250 RPM to 1750 RPM at constant torque constitutes the second instance of transient operation. Figure 6.9(a) depicts the speed waveform for a duration of 10 seconds. It is observed that the system settles down at the new speed within 0.5 seconds.

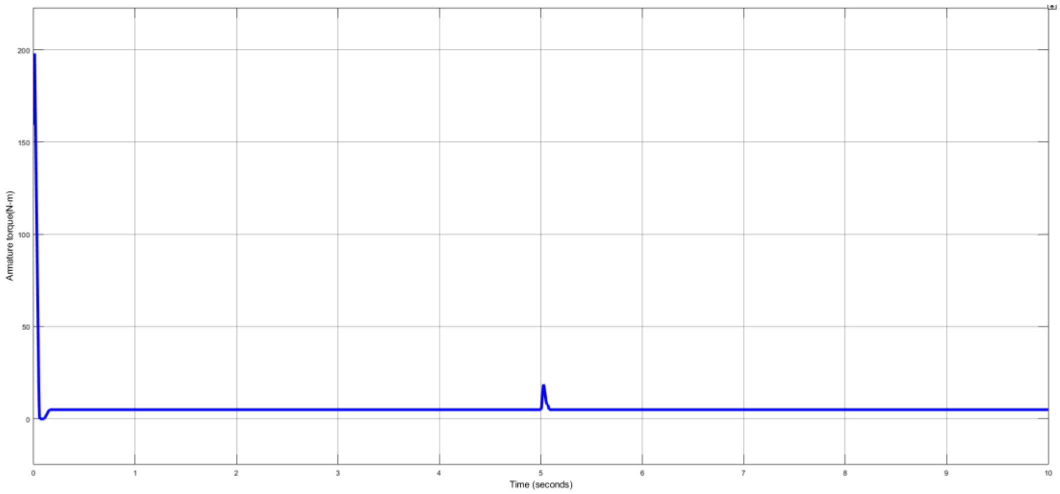
The momentary change in armature torque caused by a sudden alteration in the speed is seen in Figure 6.9(c). The characteristics of current that is identical to that of torque is shown in figure 6.9(b). The change in armature voltage with respect to the change in motor speed is depicted in figure 6.9(d). As seen in figure 6.9(e), when the speed increases, the motor draws more energy from the source, resulting in a fall in the SoC of the battery by 0.08%. The battery voltage and current during this phase are depicted.



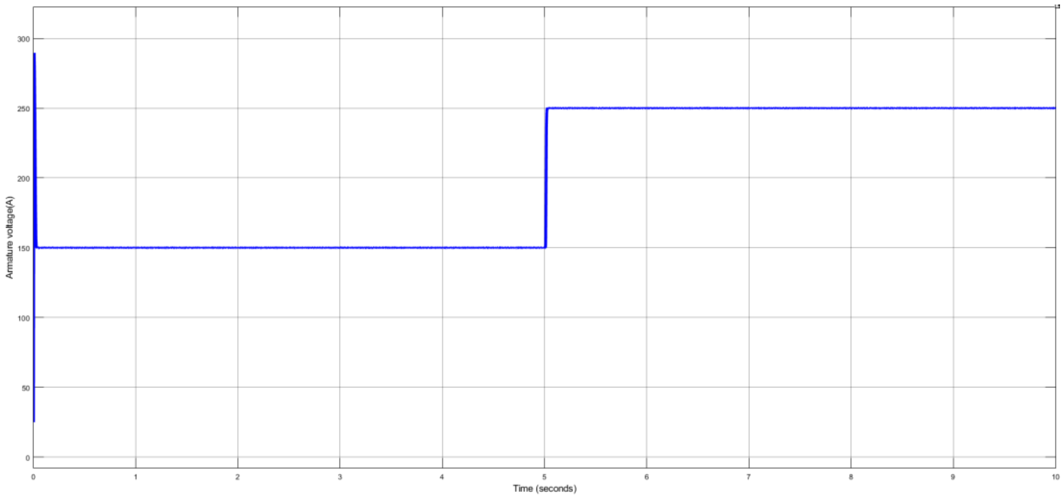
(a)



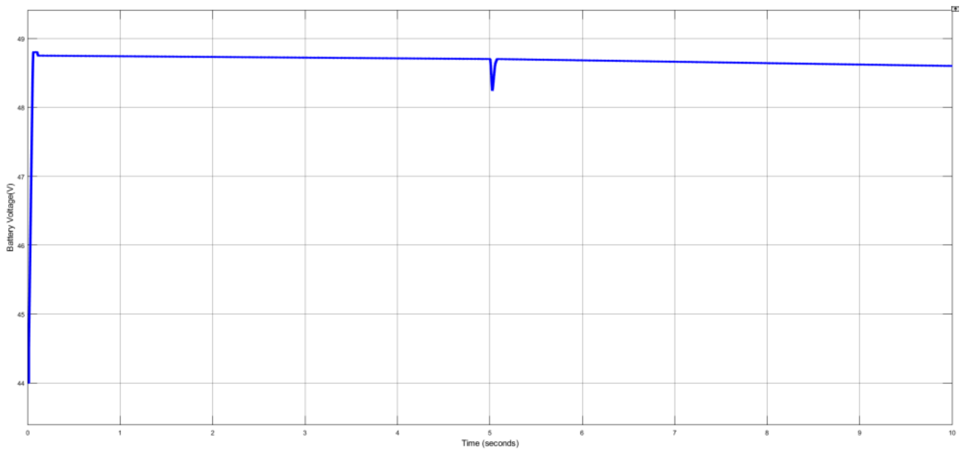
(b)


Armature torque(N-m)
Time (seconds)

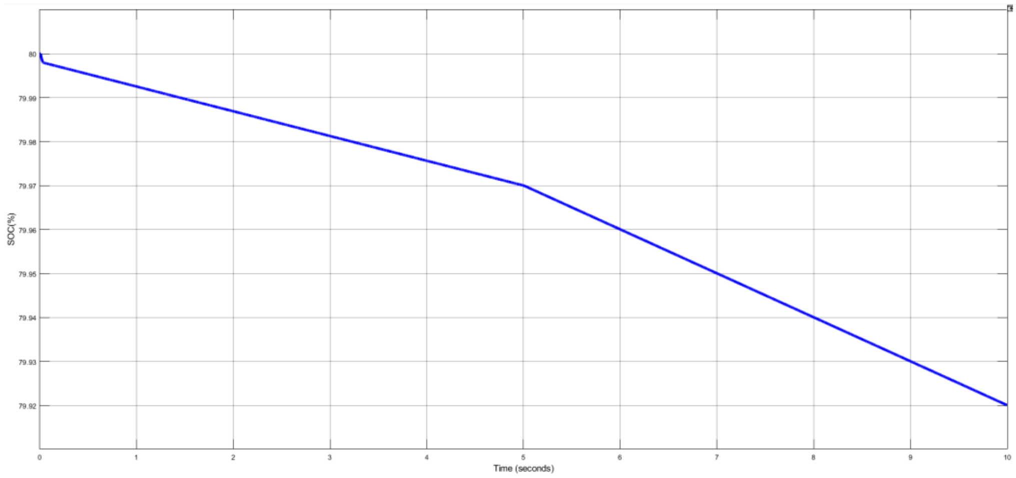
(c)


Armature voltage(A)
Time (seconds)

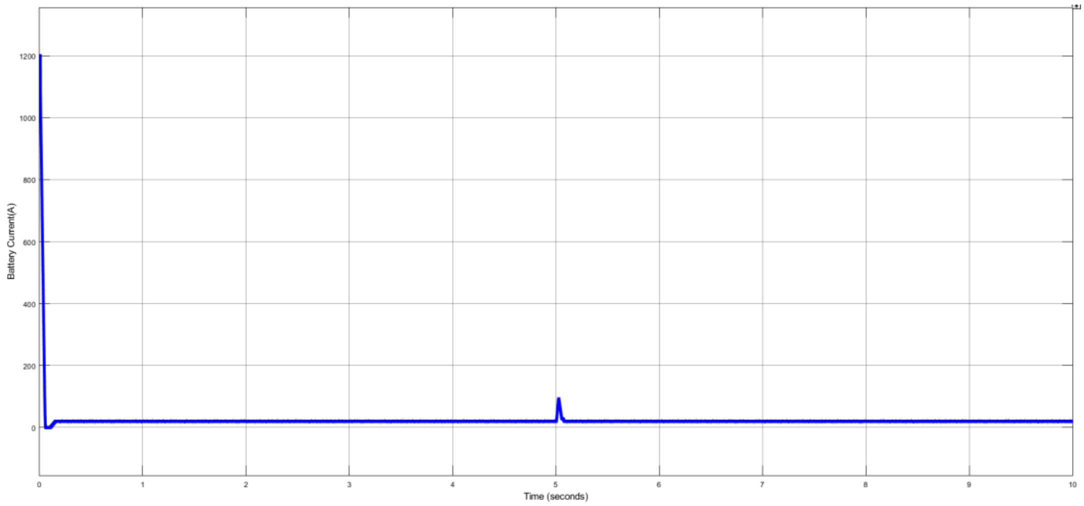
(d)


Battery Voltage(V)
Time (seconds)

(e)



(f)



(g)

FIGURE 6.9 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

7.CONCLUSION

This research has demonstrated the potential of a high-gain bidirectional DC-DC converter fed electric vehicle drive system, equipped with a sliding mode controller (SMC), for addressing ripple distortion and improving overall system efficiency. The proposed system, through its novel use of sliding mode control, offers significant advantages over traditional control methods by providing robust regulation of voltage and current, even under varying load conditions. Ripple distortion, which is a major concern in power conversion systems, has been significantly reduced, leading to enhanced power quality and longer battery life. The high-gain converter configuration ensures that the system can efficiently handle both the charging and discharging modes, optimizing energy transfer between the battery and the motor. This approach provides better voltage regulation, especially during regenerative braking, where voltage fluctuations are more common. Furthermore, the system's dynamic response to load changes and input voltage variations has been improved, which contributes to its overall efficiency and stability. Through detailed simulations and analysis, the proposed system has shown superior performance compared to conventional systems, particularly in terms of ripple reduction, efficiency, and stability. The application of sliding mode control has proven to be effective in maintaining a high level of performance even under non-ideal conditions, demonstrating its robustness for real-world EV applications.

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