

Design and Development of a Bidirectional DC-DC Converter with DC Motor Drive for Electric Vehicle Application

Bharath Kumar A¹, Parth Sarathi Panigrahy²

¹M.Tech Student, Electrical and Electronics Dept., RV College of Engineering, Karnataka, India

²Assistant Professor, Electrical and Electronics Dept., RV College of Engineering, Karnataka, India

Abstract - The increasing demand for sustainable and energy-efficient transportation has accelerated research into advanced electric vehicle (EV) technologies. This paper presents the design, simulation, and validation of a bidirectional DC-DC converter integrated with a DC motor drive system for EV applications. The proposed architecture enables efficient power management by supporting both motoring and regenerative braking modes, facilitating two-way energy flow between the battery and traction motor. A Proportional-Integral (PI) controller is employed to ensure precise speed regulation, stable voltage and current control, and seamless mode transitions. Comprehensive modelling is carried out in MATLAB/Simulink to analyse system dynamics under varied operating scenarios, including acceleration, constant-speed cruising, and deceleration. Simulation results confirm that up to 25% of braking energy can be recuperated and stored, extending the vehicle's range and improving battery utilization. A laboratory prototype further validates the simulation, demonstrating close alignment in current, voltage, and speed profiles. The study affirms the practical viability of bidirectional converter technology in next-generation EV powertrains, highlighting significant gains in energy efficiency, operational flexibility, and environmental sustainability.

Index Terms: EV, DC, AC, PI, PMDC, PWM, MOSFETs, SOC.

1. INTRODUCTION

The rapid expansion of electric mobility is driven by the dual imperatives of reducing greenhouse gas emissions and improving energy resource sustainability in the transportation sector. Electric vehicles (EVs), leveraging advances in power electronics and battery storage, have become a focal point of both industry and academic research. Central

to their widespread adoption are the challenges of optimizing energy conversion, extending driving range, and achieving seamless drive control under diverse operational conditions. A crucial technology enabling such advancements is the bidirectional DC-DC converter, which allows for efficient two-way energy flow between the vehicle's battery and electric drive system. When integrated with a robust DC motor drive and an intelligent control strategy, such a converter not only ensures dependable propulsion but also facilitates regenerative braking—recapturing kinetic energy during deceleration and feeding it back into the battery. The present research addresses the design, simulation, and experimental validation of a bidirectional DC-DC converter-based DC motor drive system. System performance is rigorously investigated in terms of dynamic drive control, energy recovery during braking, and overall efficiency improvements, providing insights relevant to the next generation of high-performance EV powertrains.

1.1 Overview

This paper proposes and validates a bidirectional DC-DC converter architecture paired with a DC motor drive for electric vehicle applications. The system is engineered to support both motoring (battery-to-motor) and regenerative braking (motor-to-battery) modes, thus enhancing energy utilization and extending the vehicle's operational range. The core control scheme employs a Proportional-Integral (PI) controller for precise speed and current regulation, ensuring rapid response and stability across both operating regimes. Detailed modeling and simulation are conducted using MATLAB/Simulink, enabling dynamic analysis under various real-world driving profiles. Key metrics—including energy recovery

rates, system efficiency, and transient performance—are benchmarked through both simulation and laboratory experimentation using a dedicated hardware prototype. The results confirm that the bidirectional converter system can recuperate a significant portion of braking energy, achieve high control fidelity, and align closely with theoretical predictions. This integrated approach offers a scalable and practical solution, paving the way for more energy-efficient, reliable, and sustainable EV platforms.

2. METHODOLOGY AND BLOCK DIAGRAM

- Requirement Analysis & System Specification:** The project commenced with a detailed analysis of electric vehicle (EV) drive requirements, focusing on target vehicle performance, battery specifications, DC motor ratings, and desired control features. Relevant standards and benchmarks for regenerative braking efficiency and system safety were studied to define design constraints.
- System Modelling & Block Diagram Development:** A comprehensive block diagram was created to capture the functional architecture of the system. Key subsystems identified include the power source (battery), bidirectional DC-DC converter, DC motor, feedback sensors, PWM-based control unit (PID/PI controller), and user input interface.
- Power Electronics & Converter Design:** The bidirectional DC-DC converter was mathematically modelled for both motoring and regenerative modes. Component sizing was based on input/output voltage, current, and efficiency targets. Simulation models were built in MATLAB/Simulink to predict system behavior and validate circuit choices under varied operating conditions.
- PI Controller Development & Programming:** A Proportional-Integral (PI) speed and current controller was designed to ensure stable, smooth motor control and precise transition between driving and braking. Control algorithms were coded (e.g., for Arduino or STM32), and PWM signal generation logic implemented to drive MOSFET gates in the converter.

- Sensor Selection & Feedback Integration:** Voltage, current, and speed sensors were selected and integrated in the control feedback loop. Accurate and fast feedback was ensured for effective closed-loop control of speed and torque.
- Simulation Testing & Validation:** Extensive simulations were performed to assess performance during various dynamic events: acceleration, constant-speed operation, and regenerative braking. Hardware tests involved real-time measurement of speed, current, voltage, and SOC. Results from physical tests were compared to simulation data for validation and refinement.
- Result Analysis & Optimization:** System performance—such as regenerative energy recovery, efficiency, and controller response—was analysed. Findings were benchmarked against initial targets, and design parameters were iteratively optimized to maximize vehicle range and reliability.

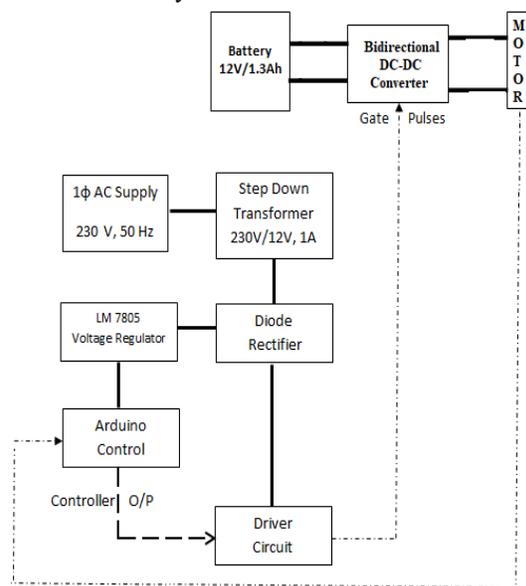


Fig -1: Block Diagram

The block diagram shown in Fig. 1 illustrates the proposed system for electric vehicle drive integrates a rechargeable battery, a bidirectional DC-DC converter, and a DC motor under the supervision of a microcontroller-based control scheme to enable both motoring and regenerative braking functionalities. The process begins with an AC supply, stepped down and rectified to provide regulated DC power for the

control electronics, notably the Arduino microcontroller. The microcontroller executes a PI-based control algorithm, receiving real-time feedback from the system and generating PWM signals for precise switching of the converter. These signals are amplified by a driver circuit, which safely actuates the MOSFET switches within the bidirectional converter to govern energy flow. In motoring mode, energy is delivered from the battery to the motor for propulsion, while in regenerative mode, triggered during braking, the motor operates as a generator, enabling recovered energy to be efficiently routed back to recharge the battery. Throughout, closed-loop feedback ensures stable operation, accurate speed control, and system protection, thereby maximizing energy efficiency, extending driving range, and validating the robustness and adaptability of the integrated EV drive architecture.

2.1 Design Specifications

The design phase of the electric vehicle drive system incorporates a rechargeable lithium-ion battery rated at 48 V and 22 A capacity, selected for its high energy density and ability to support sustained motoring and regenerative charging cycles. The core power electronics element is a half-bridge bidirectional DC-DC converter employing fast-switching MOSFETs rated suitably above 60 V and 40 A to accommodate dynamic current demands and ensure system reliability under both motoring and regenerative braking modes. The converter’s passive components include an inductor of approximately 0.108 mH to minimize current ripple and facilitate efficient energy transfer, alongside a 6.5 mF capacitance to stabilize output voltage and suppress high-frequency noise. Switching frequency is set at 5 kHz, optimized to balance converter efficiency and transient response while thermal management strategies, such as heatsinks, are implemented to manage MOSFET heat dissipation during continuous operation.

Simulation Parameters		Values
Battery	Voltage	12V
	Capacity	7.5 Ah
Boost Converter	inductance	0.108mH
	Capacitance	6.5mF
	Switching frequency	5KHz
DC Motor	Voltage	48V
	current	22A
	speed	1500 rpm
	Torque	6.3 Nm

Armature Resistance	0.6Ω
Armature Inductance	12mH

Table -2: Switching Mode

The drive motor selected is a separately excited Permanent Magnet DC motor rated for 48 V, 22 A, with nominal speed and torque specifications of 1500 rpm and 6.3 Nm respectively, possessing armature resistance of 0.6 Ω and inductance of 12 mH to model accurate motor dynamics. Control is realized through a microcontroller platform (e.g., Arduino Uno), executing a Proportional-Integral (PI) control algorithm for precise speed and current regulation. Accurate feedback is provided by speed and current sensors, enabling closed-loop control with high-frequency pulse width modulation for the converter’s switching signals. Auxiliary circuitry includes a voltage-regulated 5 V DC supply for control logic and driver circuits that provide safe signal amplification and isolation for MOSFET gate driving. Protection mechanisms such as fuses, relays, and fault detection are incorporated to safeguard against overcurrent and thermal risks. The system targets an energy transfer efficiency exceeding 90% across operational modes, achieves regenerative braking energy recovery rates of 20–25%, and maintains stable, ripple-minimized voltage and current profiles to the motor, thereby optimizing overall vehicle range, performance responsiveness, and operational robustness in electric vehicle use cases.

2.2 Bidirectional DC-DC Converter

The half-bridge bidirectional DC/DC power converter shown above is considered. $T1$ and $T2$ are the switches of the topology and ($D1$ and $D2$) are the freewheeling diodes of the switches, L , $C1$, and $C2$ are the passive elements of the converter, UC is the ultra-capacitor bank and R a variable load. Since $C1$ capacitance is very small in comparison with the UC capacitance, it can be neglected.

The variable iL corresponds to the inductor current and $vc1$ and $vc2$ to the capacitors voltage, respectively. Furthermore, the DC bus is connected to the variable load (inverters that feed the AC loads); thus, the load is connected in parallel to the capacitor $C2$. This load can handle bidirectional power.

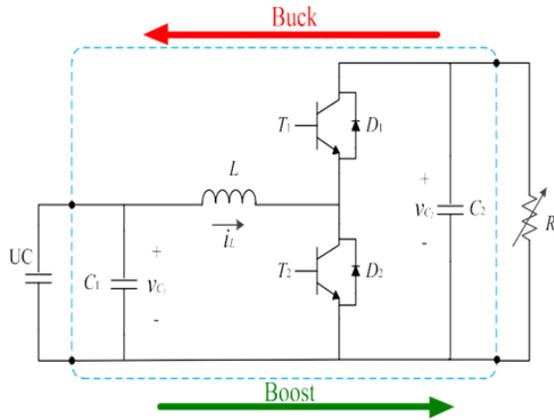


Fig -2: Bidirectional DC-DC Converter

As it can be seen, this power converter has two controlled switches (T_1 and T_2). When $T_1=OFF$ while T_2 switches ON and OFF, the power converter operates as a boost converter; and when $T_2=OFF$ while T_1 switches ON and OFF, the power converter operates as a buck converter. In boost operation the energy is transferred from battery to the load R , whereas in buck operation the energy is transferred from PV to Battery. Depending on the switch positions and the previous value of iL , denoted as (t^-).

There are four switching modes summarized below:

Operation	T_1	T_2	i_L	$i(t^-)$	Mode
Boost	OFF	ON	↑	$[-i_{Lp}, i_{Lmax}]$	1
	OFF	OFF	↓	$[0, i_{Lmax}]$	2
Buck	ON	OFF	↓	$[-i_{Lmax}, i_{Lmax}]$	3
	OFF	OFF	↑	$[-i_{Lmax}, 0]$	4

Table -2: Switching Mode

3. SIMULATION ANALYSIS AND RESULTS

The MATLAB/Simulink simulation of design and experimental validation of a bidirectional DC-DC converter-based DC motor drive for electric vehicle (EV) applications integrates both hardware and embedded control frameworks. The system is architected to enable two-way energy flow between a rechargeable battery and a DC motor, facilitating both motoring (propulsion) and regenerative braking (energy recuperation) operations. The major subsystems include the energy source (battery), bidirectional converter, DC motor, sensor feedback network, and the central control unit, which is implemented using an Arduino microcontroller.

3.1 Simulation Circuit

The presented block diagram illustrates the comprehensive architecture of an electric vehicle (EV) drive system powered by a bidirectional DC-DC converter and a Permanent Magnet DC (PMD) motor, coordinated through a microcontroller-based control unit. At its core, the circuit ensures efficient and controlled energy flow between a rechargeable battery and the traction motor, enabling both motoring (driving) and regenerative braking (energy recovery) operations—key features for modern EVs emphasizing energy efficiency and sustainability.

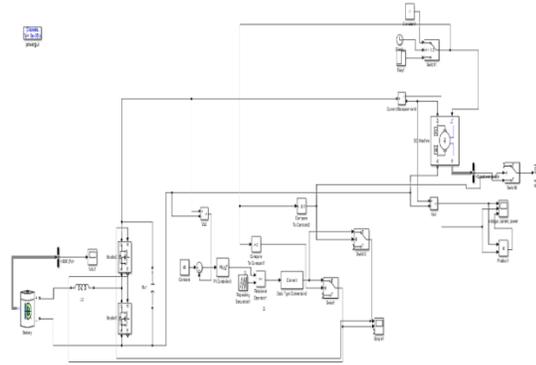


Fig -3: Simulation Block Diagram

Power to the control and auxiliary circuits is initially supplied from a single-phase AC source, which is stepped down by a transformer and then rectified to DC by a bridge rectifier. A voltage regulator further stabilizes the output, providing a safe and noise-free 5V DC supply ideal for sensitive digital electronics, particularly the Arduino microcontroller used here as the central control unit.

The Arduino controller continuously monitors user inputs (such as speed or direction), sensor feedback (speed, current, voltage), and system status. It executes an embedded algorithm—typically a Proportional-Integral (PI) controller—to ensure the motor speed accurately tracks the desired reference. The resultant control output modulates the duty cycle of Pulse Width Modulation (PWM) signals. These PWM signals are further conditioned and amplified by the gate driver circuit, which ensures reliable and galvanically isolated switching of the power MOSFETs within the bidirectional converter.

The bidirectional DC-DC converter acts as the central power-processing unit, channelling current between the battery and motor as required. In motoring mode, it conveys energy from the battery to the motor,

propelling the vehicle. During regenerative braking—initiated when the vehicle slows or brakes—the energy flow is reversed: the motor operates as a generator, sending electrical energy back through the converter to recharge the battery, thus increasing overall system efficiency and extending operational range.

Protective components such as fuses, relays, and hardware-level sensors (for current, voltage, and possibly temperature) are integrated to safeguard the circuit against overload, overvoltage, or short-circuit conditions, thereby ensuring system reliability and safety. The feedback loop—spanning from sensors through the microcontroller back to the converter—constitutes a closed-loop control system, delivering precise, real-time regulation of speed, torque, and energy flow under varying loads and driving conditions.

The Permanent Magnet DC motor is the electromechanical actuator converting DC electrical energy into mechanical rotational energy (torque and speed), propelling the vehicle. During braking, it also functions as a generator, converting decelerative kinetic energy into electrical energy for recharge.

This unit is the “brain” of the system. It receives inputs (such as desired speed or braking command), processes real-time feedback from sensors (motor speed, current, voltage), and executes control algorithms (e.g., PI/PWM control). It generates the appropriate gate drive signals to the converter’s MOSFETs to regulate motor speed and mode transitions efficiently.

These sensors provide essential feedback for safe, stable, and accurate closed-loop control. Current sensors monitor battery and armature currents to prevent overcurrent situations; voltage sensors ensure all subsystems operate within safe voltage levels; speed sensors enable precise motor speed regulation and assist in switching between motoring and braking modes.

Each part plays a key role—energy storage (battery), efficient and reversible power processing (bidirectional converter), electromechanical actuation/generation (DC motor), intelligent supervision (controller), robust signal transfer (driver), essential feedback (sensors), regulated power for control electronics (auxiliary supply), and electrical protection (fuses)—together forming a safe,

efficient, and highly controllable EV drive system with regenerative braking capability.

In summary, this design leverages coordinated power electronics and embedded control to realize a compact and flexible EV drive solution. It not only provides smooth propulsion and accurate speed control, but also recovers and recycles energy during braking events, thereby contributing to sustainable and energy-conscious electric mobility.

3.1 Simulation Results

The figures shows presented results rigorously demonstrate the successful realization of a bidirectional DC-DC converter integrated with a DC motor drive, controlled by a PI algorithm. The converter effectively supports power flow in both motoring and regenerative braking modes, improving energy efficiency as evidenced by load and battery SOC profiles. The system’s rapid and stable responses to braking commands underscore the validity of the control strategy. Most importantly, the observable recovery of energy during regenerative events underscores the system’s potential to extend vehicle range and reduce operational costs—thus fulfilling the primary objectives of the project and contributing to the advancement of sustainable electric mobility solutions. The fig 5.6 presents three critical waveforms: load voltage, load current, and load power. The voltage waveform initially displays oscillations as the system starts, indicative of converter switching and transient motor response. The voltage stabilizes after the initial transient—this steady region confirms that the converter and controller maintain the required DC voltage for the motor drive during normal operation. Subsequent abrupt changes and settling behavior indicate mode transitions—such as the application of regenerative braking. The final voltage collapse signals system shutoff or test end.

Initially, a peak load current is observed—an expected response as the motor overcomes inertia and accelerates. The current then levels off, reflecting the steady-state running of the motor at constant speed and torque. A sharp negative dip occurs just after one second, corresponding to the initiation of regenerative braking. Here, the motor switches from consuming current to acting as a generator, sending current back toward the battery—demonstrating successful regenerative operation.

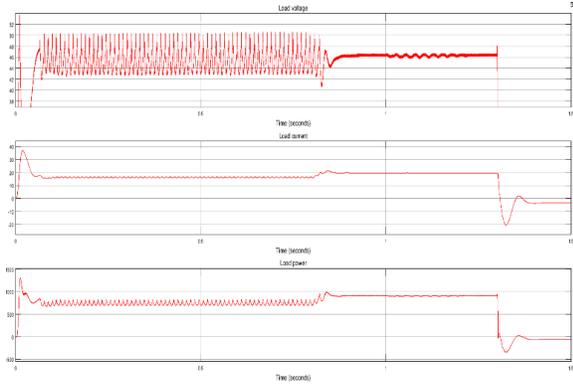


Fig-4: Output Results of Load Voltage, Current and Power

The voltage stabilizes after the initial transient—this steady region confirms that the converter and controller maintain the required DC voltage for the motor drive during normal operation. Subsequent abrupt changes and settling behavior indicate mode transitions—such as the application of regenerative braking.

The final voltage collapse signals system shutoff or test end. The power profile mirrors the current and voltage events. During acceleration, power rises, then levels with steady driving. During braking, power dips below zero, clearly showing negative power flow—confirming that energy is being returned to the battery during braking events. This is a direct indicator of regenerative energy recovery.

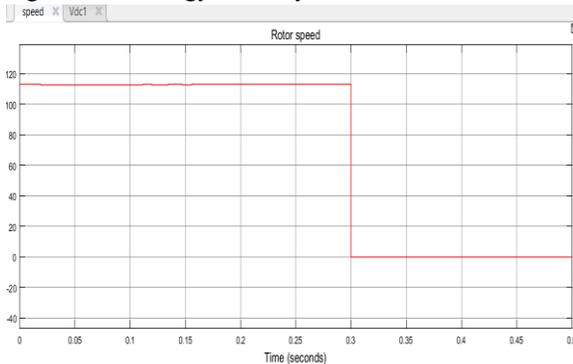


Fig-5: Output Result of Speed

This fig 5 shows the motor’s speed over time.

- The rotor maintains a high, stable speed at the beginning, indicating effective speed control during normal motoring mode.
- At approximately 0.3 seconds, there is a rapid decrease in speed, confirming a braking event—this is when the controller signals regenerative braking, and the system harnesses kinetic energy.

- Post-braking, speed drops to near zero or reverses, illustrating the transition from propulsion to deceleration.

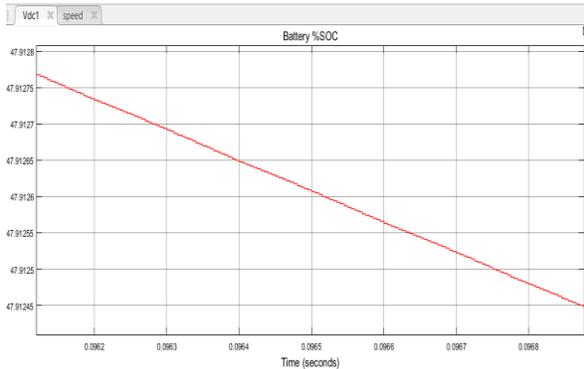


Fig-6: Output Results of state-of-charge (SOC)

This fig 6 plot depicts the battery’s state-of-charge (SOC) percentage over a brief time span.

- The slight but steady decline indicates battery discharge during motoring. The rate of SOC drop reflects the system current draw and energy usage.
- During braking, (not shown in this zoomed section) you would expect to see the SOC decrease slow or even briefly reverse, indicating that energy is being returned to the battery.

4. CONCLUSIONS

This research has presented the comprehensive design, simulation, and experimental validation of a bidirectional DC-DC converter integrated with a DC motor drive for electric vehicle (EV) applications, emphasizing the implementation and practical advantages of regenerative braking. The proposed architecture demonstrates robust bidirectional energy flow, facilitating seamless transitions between motoring and braking modes, and enabling significant recovery of kinetic energy during deceleration events. The closed-loop control strategy, based on a Proportional-Integral (PI) algorithm, has proven effective in maintaining stable motor performance, minimizing transient disturbances, and ensuring accurate speed tracking under dynamic load conditions.

ACKNOWLEDGEMENT

I express my sincere gratitude to all those who supported and guided me throughout the successful

completion of this project. I would like to thank my guide and mentor, Dr. Parth Sarathi Panigrahy, for his constant encouragement, expert guidance, and valuable feedback, which played a crucial role in shaping this work.

I would also like to thank the Head of the Department and all the faculty members of Department of EEE, RV College of Engineering, for their constant encouragement and academic support, which laid the foundation for the successful execution of this work. Their guidance has been instrumental in strengthening my technical and analytical skills.

REFERENCE

- [1] Premananda Pany, R. K. Singh and R.K. Tripathi “Bidirectional DC-DC converter fed drive for electrical vehicle system” *International Journal of Engineering, science and technology*, vol.3, no.3, 2011, pp 101-110.
- [2] B. Wang *et al.*, “Electrical Safety considerations in large-scale electric vehicle charging stations,” *IEEE Transactions on Industry Applications*, vol. 55, no. 6, pp. 6603–6612, 2019.
- [2] Y. Ma, Z. Wang, H. Yang, and L. Yang, “Artificial intelligence applications in the development of autonomous vehicles: A survey,” *IEEE/CAA Journal of Automatica Sinica*, vol. 7, no. 2, pp. 315–329, 2020.
- [3] F. J. Gomez Navarro *et al.*, “DC-DC linearized converter model for faster simulation of lightweight urban electric vehicles,” *IEEE Access*, vol. 8, pp. 85380–85394, 2020.
- [4] F. Mocera, E. Vergori, and A. Soma, “Battery performance analysis for working vehicles applications,” *IEEE Transactions on Industry Applications*, vol. 56, no. 1, pp. 644–653, 2020.
- [5] S. Alshahrani, M. Khalid, and M. Almuahini, “Electric vehicles beyond energy storage and modern power networks: Challenges and applications,” *IEEE Access*, pp. 99031–99064, 2019.
- [6] A. Affam, Y. M. Buswig, A. K. B. H. Othman, N. B. Julai, and O. Qays, “A review of multiple input DC-DC converter topologies linked with hybrid electric vehicles and renewable energy systems,” *Renewable and Sustainable Energy Reviews*, vol. 135, Jan. 2021, Art. no. 110186.
- [7] M. Z. Hossain, N. A. Rahim, and J. a/l Selvaraj, “Recent progress and development on power DC-DC converter topology, control, design and applications: A review,” *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 205–230, Oct. 2017.
- [8] A. Khaligh and M. D’Antonio, “Global trends in high-power onboard chargers for electric vehicles,” *IEEE Transactions on Vehicular Technology*, vol. 68, pp. 3306–3324, Apr. 2019.
- [9] F. Mumtaz *et al.*, “Review on non-isolated DC-DC converters and their control techniques for renewable energy applications,” *Ain Shams Engineering Journal*, vol. 12, pp. 3747–3763, Dec. 2021.
- [10] M. A. Hannan, M. M. Hoque, A. Mohamed, and H. Ayob, “Review of energy storage systems for electric vehicle applications: Issues and challenges,” *Renewable and Sustainable Energy Reviews*, vol. 69, pp. 771–789, Mar. 2017.
- [11] D. Das, A. Mahapatra, and B. Subudhi, “A survey on DC–DC converter control techniques for renewable energy applications,” *Renewable and Sustainable Energy Reviews*, vol. 76, pp. 941–954, Sep. 2017.
- [12] T. Dragicevic, J. M. Guerrero, J. C. Vasquez, and D. Skrlec, “Supervisory control of an adaptive-droop regulated DC microgrid with battery management capability,” *IEEE Transactions on Power Electronics*, vol. 29, no. 2, pp. 695–706, 2014.
- [13] B. Wang *et al.*, “Electrical Safety considerations in large-scale electric vehicle charging stations,” *IEEE Transactions on Industry Applications*, vol. 55, no. 6, pp. 6603–6612, 2019.