A

Project Stage – II Report

on

"A MODIFIED FUZZY LOGIC CONTROLLER BASED HIGH CURRENT DENSITY DC-DC CONVERTER FOR EV CHARGING APPLICATIONS"

Submitted to

Jawaharlal Nehru Technological University, Hyderabad, for the partial fulfillment of the requirement for the award of degree of

BACHELOR OF TECHNOLOGY

IN

ELECTRICAL AND ELECTRONICS ENGINEERING

by

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JYOTHISHMATHI INSTITUTE OF TECHNOLOGY AND SCIENCE

(AUTONOMOUS)

(Approved by AICTE, New Delhi, Affiliated to JNTU, Hyderabad)

Accredited with NAAC 'A' Grade & NBA

Nustulapur, Karimnagar, Telangana-505527

(2021-2025)

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DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

CERTIFICATE

This is to certify that **N. ANILA (22275A0217), MD. AMEERKHAN (22275A0210), B. MADHU (22275A0214), SD. FEROZ (22275A0212)** have successfully completed the Project Stage – II entitled as **"A MODIFIED FUZZY LOGIC CONTROLLER BASED HIGH CURRENT DENSITY DC-DC CONVERTER FOR EV CHARGING APPLICATIONS"** for the partial fulfilment of the requirements for the award of degree of **Bachelor of Technology** in **Electrical and Electronics Engineering** during the academic year **2024-2025** under our guidance and supervision.

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DECLARATION

We hereby declare that the work which is being presented in this Project Stage-II entitled as **"A MODIFIED FUZZY LOGIC CONTROLLER BASED HIGH CURRENT DENSITY DC-DC CONVERTER FOR EV CHARGING APPLICATIONS"** submitted towards the partial fulfilment of the requirements for the award of the degree of **Bachelor of Technology** in **Electrical and Electronics Engineering**, Jyothishmathi Institute of Technology and Science, Karimnagar is an authentic record of our own work carried out under the supervision of **Mr. CH. SAJAN RAO,** Associate Professor, Department of Electrical and Electronics Engineering.

To the best of our knowledge and belief, this project bears no resemblance with any report submitted to Jawaharlal Nehru Technological University, Hyderabad or any other university for the award of any degree.

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ABSTRACT

This paper presents a novel modified fuzzy logic controller (FLC)-based high current density DC–DC converter for electric vehicle (EV) charging applications. With the growing demand for electric vehicles, an efficient and reliable charging system is critical to their adoption and use. The high current density converter, driven by an advanced fuzzy logic control technique, is designed to address the needs of modern EV charging stations, which require high efficiency, fast charging times, and optimal performance across a variety of input and load conditions. The proposed system aims to improve the conventional control schemes by incorporating fuzzy logic, which allows for more flexible and adaptive control compared to traditional linear controllers. The system is modeled and analyzed for its effectiveness in various scenarios, including load variations and input voltage fluctuations, ensuring that the charging process is both fast and reliable. Simulation results confirm the superior performance of the proposed system, showing improved efficiency and reduced power losses compared to traditional controllers.

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CHAPTER-1

INTRODUCTION

1.1 Context

A controller-based high current density DC-DC converter plays a vital role in electric vehicle (EV) charging applications by enabling efficient and reliable energy transfer from power sources to EV batteries. These converters are specifically designed to handle high levels of current in a compact form, which is essential for reducing the size and weight of EV chargers while maintaining high performance. The implementation of advanced control strategies in such converters ensures precise regulation of output voltage and current, system stability, fast dynamic response, and improved efficiency under varying load conditions.

In EV charging systems, the DC-DC converter is responsible for converting the input DC voltage—typically from the grid (through an AC-DC front end) or from renewable energy sources—into the required output voltage and current suitable for charging the EV battery. The converter must be capable of operating over a wide input and output range to accommodate different battery voltages and state-of-charge levels. Controller-based converters also enable bidirectional power flow, allowing energy to be both stored in and extracted from the battery, which is a key feature for vehicle-to-grid (V2G) and vehicle-to-home (V2H) applications.

Several converter topologies are used in high current density applications. Interleaved buck converters are commonly employed due to their ability to share current between phases, reduce ripple, and improve thermal distribution. Isolated topologies such as full-bridge and half-bridge converters are preferred when galvanic isolation is required, especially in offboard charging stations where safety is a major concern. Bidirectional converters are gaining popularity for their ability to facilitate both charging and discharging operations, essential for modern smart grid integration.

The choice of control strategy significantly impacts the performance of the converter. Proportional-Integral-Derivative (PID) controllers are simple and widely used but may not perform well under rapidly changing load conditions or nonlinearities. To overcome these limitations, advanced controllers such as Fuzzy Logic Controllers (FLC) and Sliding Mode Controllers (SMC) are used. FLCs offer robustness and adaptability to nonlinear and time-varying systems, while SMCs provide strong disturbance rejection and fast dynamic response. Model Predictive Control (MPC) is another advanced technique that optimizes future system behaviour based on a mathematical model, making it suitable for high-performance EV chargers.

Digital control platforms such as Digital Signal Processors (DSPs), Field Programmable Gate Arrays (FPGAs), and microcontrollers are widely adopted for real-time implementation of complex algorithms. These platforms support high switching frequencies and enable integration of multiple functionalities such as power factor correction, fault detection, and communication with battery management systems (BMS). Efficient thermal management and electromagnetic interference (EMI) reduction are also critical design aspects, especially when dealing with high current levels.

In conclusion, controller-based high current density DC-DC converters are essential for efficient, compact, and intelligent EV charging systems. Their ability to manage high power levels with precise control, ensure system safety, and support grid interaction makes them a core component in the development of sustainable electric mobility infrastructure.

The demand for fast and reliable electric vehicle (EV) charging has significantly increased the need for advanced DC-DC converters with high current density and intelligent control systems. These converters are at the heart of EV charging stations and onboard chargers, enabling the transformation of electrical energy from the supply source into a form suitable for charging batteries efficiently and safely. High current density refers to the ability of the converter to deliver large amounts of current in a compact physical size, which is essential for reducing space and improving power-to-volume ratios, especially in portable or onboard EV charging systems.

In high-performance EV charging, the controller plays a critical role in governing the operation of the DC-DC converter. It continuously monitors various parameters such as input voltage, output voltage, current, temperature, and battery state of charge, and adjusts the switching signals accordingly to maintain optimal operation. A well-designed controller ensures accurate output regulation, protects the system from faults, and enhances the overall efficiency of power conversion, which is crucial for reducing energy losses and extending the lifespan of both the converter and the battery.

Different converter topologies offer specific advantages depending on the application. For example, an interleaved buck converter, which consists of multiple parallel phases operating out of phase, helps in reducing current ripple, improving thermal management, and increasing the overall power output. This makes it ideal for applications where high current and low output voltage are required. On the other hand, isolated topologies such as full-bridge and LLC resonant converters are used in fast offboard charging stations where galvanic isolation between the input and output is mandatory for safety. These converters also support high efficiency over a wide load range due to soft-switching capabilities.

The integration of bidirectional DC-DC converters in EV systems supports both charging and discharging operations, enabling features like regenerative braking and vehicle-to-grid (V2G) energy sharing. This functionality requires sophisticated control strategies to manage bidirectional power flow while ensuring voltage and current are kept within safe limits. Controllers must respond swiftly to direction changes and maintain high efficiency during both modes of operation.

Advanced control strategies such as fuzzy logic, sliding mode control, and model predictive control offer superior performance over conventional linear controllers in complex, nonlinear environments like EV charging. Fuzzy logic controllers are rule-based systems that can handle uncertainties and adapt to varying conditions without requiring precise mathematical models. Sliding mode control provides robustness against parameter variations and disturbances, ensuring stable operation. Model predictive control uses optimization algorithms to anticipate future behavior and adjust control actions proactively, making it suitable for real-time high-power applications.

Digital implementation of these control techniques using microcontrollers, DSPs, or FPGAs allows for high-speed operation and flexibility in design. These platforms enable real-time monitoring, diagnostics, and communication with other vehicle systems like the battery management system (BMS) and thermal management units. Additionally, they support features such as fault detection, thermal protection, and power quality management.

1.2 Importance of High Current Density in DC-DC Converters

High current density is a crucial design parameter in modern DC-DC converters used for EV charging. It refers to the ability of a converter to handle high levels of current within a compact physical size. This is especially important in EV applications where space and weight are limited, such as in onboard chargers. High current density allows for faster charging times, which directly impacts user convenience and vehicle turnaround time. To achieve this, engineers use advanced materials and components like wide-bandgap semiconductors (SiC and GaN), which can operate at higher switching frequencies and temperatures with lower losses.

Optimized magnetic components and cooling systems are also critical. Higher current densities lead to increased thermal stress, so efficient thermal management is essential to prevent overheating and ensure long-term reliability. In summary, high current density contributes to making EV chargers more powerful, compact, and efficient.

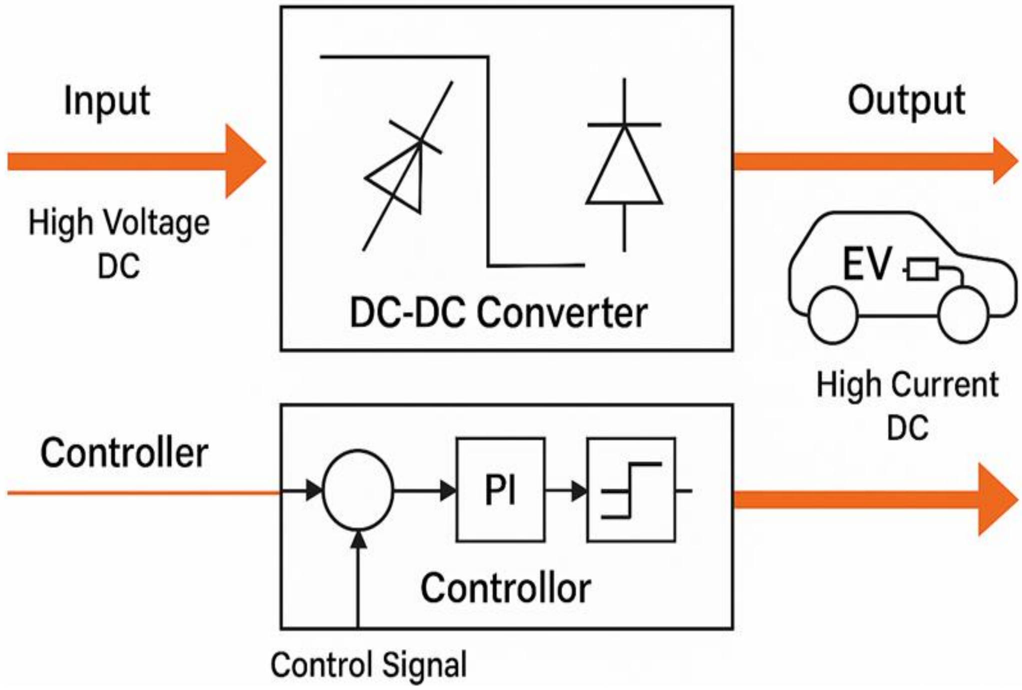

Figure 1: Controller-based High Current Density DC-DC Converter for EV charging applications

1.3 Role of Controllers in Power Regulation and System Stability

Controllers are the brains of DC-DC converters. Their primary role is to maintain regulated output voltage and current to match the battery's charging profile, despite changes in input conditions, load, or temperature. In EV charging, the controller continuously monitors feedback signals such as output voltage, current, and battery state, and dynamically adjusts the duty cycle of the switching elements (usually MOSFETs or IGBTs). This feedback loop ensures the power delivered is accurate and stable. Beyond regulation, controllers are responsible for system stability—preventing oscillations or overshoots that can damage the battery or converter. They also implement protection mechanisms for faults such as overvoltage, short circuits, and overtemperature. Advanced digital controllers can adapt in real time to changing operating conditions, improving reliability and charging efficiency.

1.4 Common DC-DC Converter Topologies for EV Charging

Common DC-DC converter topologies used for EV charging applications include Buck, Boost, Buck-Boost, Cuk, SEPIC (Single-Ended Primary-Inductor Converter), and Full-Bridge Converters. The Buck converter steps down the input voltage, making it suitable for voltage regulation in onboard chargers. The Boost converter increases the input voltage, ideal for interfacing with low-voltage energy sources like solar panels. The Buck-Boost converter can either step up or step down the voltage, providing greater flexibility for varying input conditions. Cuk converters offer smooth input and output current with the ability to invert voltage, while SEPIC converters allow both step-up and step-down capabilities without inverting the output. For high-power EV charging, Full-Bridge converters are commonly used due to their high efficiency and ability to handle high power levels with galvanic isolation. These topologies are selected based on power rating, efficiency requirements, isolation needs, and the specific characteristics of the EV charging infrastructure.

Various DC-DC converter topologies are employed based on the EV charger's power level, isolation requirements, and system complexity:

- **Buck Converter:** The Buck converter is a step-down DC-DC converter that reduces the input voltage to a lower output voltage while maintaining the current. It is widely used in onboard chargers to regulate the voltage for battery charging. Its simple design and high efficiency make it ideal for low-power applications where voltage reduction is necessary. However, it does not provide isolation, which limits its use in scenarios requiring electrical separation between the source and load.
- **Boost Converter:** The Boost converter is a step-up DC-DC converter that increases the input voltage to a higher output voltage. This topology is particularly useful in EV charging when power from low-voltage sources, such as solar panels or regenerative braking systems, needs to be raised to match the battery's charging requirements. Its high efficiency and straightforward design allow it to handle significant power levels, although it lacks isolation.
- **Buck-Boost Converter:** The Buck-Boost converter is versatile, capable of both stepping up and stepping down the input voltage, depending on the duty cycle. This adaptability makes it ideal for EV applications where fluctuating input voltages are present. It can maintain a stable output even with varying input sources, but its design

is slightly more complex than individual Buck or Boost converters. It can produce either a positive or negative voltage output depending on its configuration.

- **Cuk Converter:** The Cuk converter is a unique topology that provides both step-up and step-down capabilities while maintaining continuous current on both input and output sides. It features an inverting operation, meaning the output voltage is of the opposite polarity to the input. The Cuk converter is valued for its low ripple current, which enhances efficiency and reduces electromagnetic interference (EMI) in EV chargers. However, its design is more complex due to the use of additional components like inductors and capacitors.
- **SEPIC Converter:** The Single-Ended Primary-Inductor Converter (SEPIC) is another non-isolated topology that can step up or step down the input voltage without inverting its polarity. SEPIC converters are popular in EV charging circuits for their ability to maintain a constant output voltage despite input variations. Its unique design, which includes two inductors and a coupling capacitor, provides smooth transitions between step-up and step-down modes, making it ideal for dynamic charging conditions.
- **Full-Bridge Converter:** The Full-Bridge converter is an isolated DC-DC converter designed for high-power EV charging applications. It uses four switches to control power flow and provides galvanic isolation through a transformer, ensuring safety and protection. Its efficiency and ability to handle high currents make it ideal for fast chargers and high-voltage battery systems. Additionally, the transformer-based design enables voltage scaling, which is essential for multi-level EV charging infrastructures.

1.5 Comparison of Control Strategies (MPI, Fuzzy, SMC, MPC)

Different control strategies are used depending on the complexity and performance requirements of the EV charger:

- **MPI Control**: The Modified Proportional-Integral (PI) controller is an enhancement of the traditional PI controller, designed to improve transient response and reduce steady-state error. It achieves better tracking and disturbance rejection by adjusting its parameters dynamically based on system behavior. However, it may struggle with nonlinearity and parameter variations in high-gain DC-DC converters, making it less adaptive in fluctuating operating conditions compared to advanced strategies like Fuzzy Logic or Model Predictive Control.

- **Fuzzy Logic Control (FLC)**: Ideal for systems with uncertainty or nonlinearity. It uses a set of heuristic rules instead of a mathematical model and is well-suited for applications where system dynamics are hard to model. The FLC is a nonlinear control strategy that handles system uncertainties and nonlinearities effectively through a rule-based approach. Unlike traditional controllers, it does not require an accurate mathematical model, making it ideal for systems with complex dynamics like DC-DC converters. FLC is robust and adaptive but may require extensive rule tuning and membership function optimization to achieve optimal performance.
- **Sliding Mode Control (SMC)**: Provides high robustness and fast response. It forces the system states to "slide" along a predefined trajectory, ensuring accurate tracking and stability, even under disturbances. SMC is a nonlinear control method known for its robustness against system disturbances and parameter uncertainties. It enforces system trajectories to slide along a predefined surface, achieving high accuracy and rapid convergence. Despite its robustness, SMC can induce high-frequency oscillations (chattering) in practical applications, which may affect the reliability of DC-DC converters without proper smoothing techniques.
- **Model Predictive Control (MPC)**: Predicts future system behavior and optimizes control actions over a prediction horizon. It handles multivariable systems constraints well but requires high computational power, typically implemented using FPGAs. MPC optimally controls system outputs by predicting future behavior over a defined horizon, adjusting control inputs accordingly. It is highly effective for systems with constraints and varying dynamics, such as high-gain DC-DC converters. MPC, however, demands significant computational resources and an accurate model for precise prediction, potentially increasing complexity for real-time applications.

1.6 Integration with Battery Management Systems (BMS)

For safe and optimized charging, the DC-DC converter must work closely with the Battery Management System. The BMS monitors the battery's voltage, temperature, state of charge (SOC), and cell balancing status. Based on this information, it communicates with the converter's controller to dynamically adjust charging parameters. For instance, during the constant current (CC) phase, the converter supplies a steady current, while during the constant voltage (CV) phase, it regulates the voltage as the battery approaches full charge. If the BMS detects a temperature rise or cell imbalance, it can signal the converter to reduce power or stop charging. This close coordination ensures the battery is charged safely and efficiently while preventing thermal runaway, overcharging, or degradation.

1.7 Summary

Controller-based high current density DC-DC converters are essential for efficient and compact EV charging systems. High current density allows these converters to deliver large currents in a small form factor, enabling fast charging while minimizing space and thermal stress. Controllers regulate the output voltage and current by processing real-time feedback and ensuring system stability, protection, and efficiency. Different converter topologies are used depending on application needs—interleaved buck converters for high current, full-bridge converters for isolation, and bidirectional converters for energy flow in both directions. Various control strategies like PID, fuzzy logic, sliding mode, and model predictive control offer different levels of performance, robustness, and complexity. Integration with the Battery Management System (BMS) is critical for safe, optimized charging, as it ensures proper voltage, temperature, and current levels are maintained throughout the charging process. Overall, these converters play a central role in the performance, safety, and intelligence of modern EV charging infrastructure.

CHAPTER-2

LITERATURE REVIEW

2.1 Analysis of Renewable Energy Sources and Electrical Vehicle Integration into Microgrid.

2.1.1 Abstract

The rise in pollution levels, leading to the emission of greenhouse gases and the subsequent phenomenon of global warming, is anticipated to stimulate the expansion of electric vehicles (EVs). Consequently, EVs will establish a connection with the electrical grid within this timeframe. The implementation of this technology will significantly influence the voltage profiles and loads of grid components. The study centered on the modeling and analysis of the integration of renewable energy sources and EVs into a microgrid. The microgrid comprises four essential elements: a diesel generator functioning as the primary power supply, a combination of a photovoltaic (PV) farm and a wind farm for generating electricity, and a vehicle-to-grid (V2G) system positioned near the microgrid's load. The continuous increase in their energy production rate makes microgrids important. Microgrids can be designed to meet the energy needs of different establishments, including hospitals, universities, and EV charging stations, as well as the energy demands of a district, town, or industrial site. Charging stations are essential for the purpose of replenishing the battery of EVs. This paper investigates the influence of EVs on the microgrid network. EVs integrate non-linear circuit components into their structures. In addition, the modeling and analysis of the renewable energy sources and EV integration into the microgrid.

2.1.2 Methodology

The paper investigates the integration of Electric Vehicles (EVs) into a microgrid system. The microgrid comprises a diesel generator, a photovoltaic (PV) farm, a wind farm, and a Vehicle-to- Grid (V2G) system. The study aims to analyze the impact of EVs on the microgrid's voltage profiles, load balancing, and grid stability. The research involves modeling and simulation using MATLAB/Simulink to assess the performance of the microgrid with varying EV penetration levels, charging patterns, and grid conditions. The findings of this research will contribute to the

development of sustainable and efficient microgrid systems that can accommodate the increasing adoption of EVs.

2.1.3 Conclusion

The incorporation of Electric Vehicles (EVs) has become an unavoidable trend in the expansion of distribution networks. The rising utilization of EVs will amplify possible issues for the distribution system. The reduction of reactive power is employed to ensure voltage regulation in the microgrid. Reactive power support enhances the power factor and diminishes power losses in power transmission lines. Furthermore, it results in heightened efficiency. EVs that are linked to the microgrid have the ability to offer reactive power adjustments. The study focuses on analyzing the operation of a standalone microgrid, specifically examining various EV charging procedures. The effects of uncertainty relate to predicted values of load demand, solar irradiation, and wind. In considering the growing prevalence of EVs, it is imperative to conduct thorough investigations on their power quality, with a particular focus on harmonic components, and implement appropriate solutions accordingly. The number of charging stations is growing steadily in direct correlation with the rising prevalence of EVs. The rapid transformation of the transportation industry in the present day necessitates the swift development of EVs, which will significantly influence both the power system and the environment.

2.2 Optimal Sizing of Renewable Energy Powered Hydrogen and Electric Vehicle Charging Station (Hevcs).

2.2.1 Abstract

The primary barrier to the extensive implementation of electric vehicles (EVs) is the lack of necessary and adequate charging infrastructure within a particular area. Moreover, sourcing the energy needed for EVs from the grid that heavily relies on fossil fuels diminishes the environmental advantages of EVs and further increases strain on the grid system in electricity-deficient regions. Therefore, this study designs and simulates six different standalone hybrid renewable energy systems utilizing solar, wind, and biomass sources and a grid-tied system for a selected location of Singa Perumal Kovil, Chennai, India. One unique aspect of this research is the use of a single station for charging electric vehicles and hydrogen refueling. These systems are designed to fulfill the energy requirements of 48 battery-electric vehicles and 17 hydrogen vehicles, using HOMER Pro software, combining a bio-gas generator, wind turbine, and photovoltaic system. The renewable energy sources are identified as the most practical and reliable among the various cases for that location, in terms of technical, economic, and environmental feasibility. Among six different standalone scenarios and a grid-tied system, the biogas generator, wind, and PV configuration model is more cost-effective than other configurations. The proposed system generates 2,009,492 kWh/yr of electricity and 30,199 kg/yr of hydrogen. The reported values for the NPC, LCOE, LCOH, and payback period were $3.46 million, $0.493/kWh, $8.86/kg, and about 3.08 years, in that order. HOMER determines the breakeven grid extension distance as 129.93km. After considering the effective rate after digestate, the NPC, LCOE, and LCOH costs are reduced to $2.90 million, $0.412/kWh, and $7.47/kg, respectively.

2.2.2 Methodology

This section outlines the approach used to achieve the goals of the study. The Hydrogen-based and Electric Vehicle Charging Station (HEVCS) is simulated to address the fuel requirements of potential electric vehicles (EVs) and hydrogen vehicles in India, focusing on Chennai as the case study. The proposed charging station is equipped with a solar PV system, wind system, biomass system, electrolyzer (for hydrogen production), hydrogen tank, electric loading (for electric vehicles), and hydrogen loading (for hydrogen vehicles). This mathematical model is designed in six different systems (scenarios 1-6) considered.

2.2.3 Conclusion

There are obstacles in the way of the growing global acceptance of electric vehicles because of the scarcity of charging stations, the high energy consumption, the load on the power grid, and the dependence on fossil fuels for electricity. Setting up standalone fully renewable energy-based charging stations is a true way to overcome these challenges. The proposed work introduces a novel facility capable of charging and refueling 48 battery-powered electric vehicles and 17 hydrogen vehicles simultaneously. One unique aspect of this research is the use of a single station for charging electric vehicles and hydrogen refueling. This study utilized biogas/biomass resources in the context of EV charging. Among the six different potential hybrid system configurations evaluated, the BG+PV+WT (scenario-6) configuration demonstrated the most significant technical, economic, and ecological viability. This leading system generates 2,009,492 kWh/yr of electricity and 30,199 kg/yr of Hydrogen. The reported values for the LCOE, NPC, LCOH, and PBP were $0.493/kWh, $3.46 million, $8.86/kg, and about 3.08 years, in that order.

The above study analyzes and compares six different standalone configurations and an on-grid system, where scenario 6 (standalone) is found to be the optimal feasible solution for this particular selected location. After considering the effective rate after digestate, the NPC, LCOE, and LCOH costs are reduced to \$2.90 million, \$0.412/kWh, and \$7.47/kg, respectively. Further, it has been observed that for a big city like Chennai, India, the proposed strategy will not only solve the charging infrastructure problems, but also provide a sustainable solution to the waste management problem. However, the availability of renewable energy sources may vary with the change in location.

2.3 Key Technologies and Prospects for Electric Vehicles within Emerging Power Systems: Insights from Five Aspects.

2.3.1 Abstract

The energy revolution requires coordination in energy consumption, supply, storage, and institutional systems. Renewable energy generation technologies, along with their associated costs, are already fully equipped for large-scale promotion. However, energy storage remains a bottleneck, and solutions are needed through the use of electric vehicles, which traditionally play the role of energy consumption in power systems. To clarify the key technologies and institutions that support EVs as terminals for energy use, storage, and feedback, the CSEE JPES forum assembled renowned experts and scholars in relevant fields to deliver keynote reports and engage in discussions on topics such as vehicle-grid integration technology, advanced solid-state battery technology, high-performance electric motor technology, and institutional innovation in the industry chain.

2.3.2 Methodology

The methodology of this research involves the design and implementation of a modified fuzzy controller-based DC-DC converter for EV charging applications. This approach integrates a modified PI controller and a fuzzy logic controller to achieve high current density with minimal overshoot and voltage fluctuations. The fuzzy logic controller optimizes the control signals to reduce power losses in the active switches and minimize junction temperature, thereby improving the converter's efficiency, reliability, and lifespan. The performance of the converter is analyzed under both ideal and non-ideal operating conditions to evaluate its robustness and reliability. Finally, a hardware prototype is implemented and tested to verify the feasibility of the converter for EV battery charging applications.

2.3.3 Conclusion

This study presented opinions on key technologies and prospects for new energy vehicles in new power systems. Specifically, Professor Ouyang emphasized the supportive role of energy storage using EVs in new power systems and its technical framework. Professor Sun proposed that ASSBS using halide electrolytes have significant potential but faces several challenges in material synthesis and manufacturing. Professor Cai introduced product innovation and technological frontiers of the industry chain in electric motor systems and highlighted the future directions of electric drive systems. Professor Song discussed the progress of global vehicle-grid integration demonstration projects, emphasizing the significance of optimizing vehicle spatiotemporal uncertainties and charging/discharging processes.

Professor Chan re-examined the profound development of EVs and addressed the importance of 4 networks and 4 flow integration. The major viewpoints of the experts are summarized below.

1. Energy storage capacity of power batteries in new energy vehicles exhibits substantial potential in both the power and energy domains. When aggregated, it is poised to emerge as the most extensive, cost-effective, and universally applicable energy storage unit. Given pronounced technological convergence between new energy power systems and new energy electric power systems, realizing an efficient V2G requires establishing high-, medium-, and low-frequency technical frameworks for grid operations, power generation and transmission, power distribution and microgrid, aggregator, and charging infrastructure.
2. Halide solid-state electrolytes are a crucial material for next-generation all-solid-state batteries. Ongoing efforts focus on improving their properties through innovative structural design and synthesis approaches. Advanced characterization techniques and theoretical simulations have been instrumental in elucidating the ion transport mechanisms of halide electrolytes and driving their development. Scaling up production remains a hurdle, with an emphasis on large-scale production and adoption of dry electrode technology to reduce costs.

2.4 Distributed Energy Resources Based Ev Charging Station with Seamless Connection to Grid.

2.4.1 Abstract

The charging of electric vehicles (EVs) via common DC bus charging infrastructure based on hybrid renewable energy sources such as solar photovoltaic (PV) and fuel cell is presented here. The requisite to incorporate renewable energy based distributed energy resources (DERs) is attributed to the escalating concern for decarbonisation with improved power quality requirements. Furthermore, the bidirectional flow of power enables the charging/discharging of EVs during the grid presence/absence modes of operation. In addition, the utilization of common DC bus charging mechanism for EVs, facilitates fast charging capability at higher voltage levels. The satisfactory operation during the grid availability/unavailability is attained through the current and voltage based control mechanisms, along with the seamless transition capability via switching (STS-1/0) of the static transfer switches. Furthermore, in compliance with the IEEE standards, the power quality (PQ) improvement is obtained with the utilization of an adaptive comb-filter based current control during the grid-tied mode of operation. The need for improving PQ, stems from the fact that an uninterrupted supply is essential to the critical loads along with an improved power quality. Thus, for validation and corroboration of the system behavior, its performance is authenticated during weak grid conditions, in conjunction with grid connected/islanded modes of operation.

2.4.2 Methodology

The methodology of this research involves the design and implementation of a modified fuzzy controller-based DC-DC converter for EV charging applications. This approach integrates a modified PI controller and a fuzzy logic controller to achieve high current density with minimal overshoot and voltage fluctuations. The fuzzy logic controller optimizes the control signals to reduce power losses in the active switches and minimize junction temperature, thereby improving the converter's efficiency, reliability, and lifespan.

The performance of the converter is analyzed under both ideal and non-ideal operating conditions to evaluate its robustness and reliability. Finally, a hardware prototype is implemented and tested to verify the feasibility of the converter for EV battery charging applications.

2.4.3 Conclusion

EVs charging mechanism with hybrid renewable energy sources, is obtained through the OPAL-RT controller (OP4510). Performances during grid connection/disconnection, load perturbation and solar radiation change are presented here and the results are recorded by using a digital storage oscilloscope.

2.5 Aging Mitigation for Battery Energy Storage System in Electric Vehicles

2.5.1 Abstract

Battery energy storage systems (BESS) have been extensively investigated to improve the efficiency, economy, and stability of modern power systems and electric vehicles (EVs). However, it is still challenging to widely deploy BESS in commercial and industrial applications due to the concerns of battery aging. This paper proposes an integrated battery life loss modeling and anti-aging energy management (IBLEM) method for improving the total economy of BESS in EVS. The quantification of BESS aging cost is realized by a multifactorial battery life loss quantification model established by capturing aging characteristics from cell acceleration aging tests. Meanwhile, a charging event analysis method is proposed to deploy the built life loss model in vehicle BESS management. Two BESS active anti-aging vehicle energy management models: vehicle to grid (V2G) scheduling and plug-in hybrid electric vehicle (PHEV) power distribution, are further designed, where the battery life loss quantification model is used to generate the aging cost feedback signals. The performance of the developed method is validated on a V2G peak-shaving simulation system and a hybrid electric vehicle. (The work in this paper presents a practical solution to quantify and mitigate battery aging costs by optimizing energy management strategies and thus can further promote transportation electrification.)

2.5.2 Methodology

This research develops an integrated approach to address battery aging in electric vehicles (EVs) by combining battery life loss modeling with anti-aging energy management strategies. A multifactorial battery life loss quantification model is established based on accelerated aging tests conducted on individual battery cells, enabling accurate assessment of aging-related costs. This model is then integrated into vehicle BESS management through a charging event analysis method. Two active anti-aging energy management strategies are designed: 1) Vehicle-to-Grid (V2G) scheduling that optimizes V2G operations while minimizing aging costs, and 2) Plug-in Hybrid Electric Vehicle

(PHEV) power distribution that optimizes power distribution between the engine and battery to minimize aging and maximize vehicle performance. The effectiveness of this integrated approach is validated through simulations of V2G systems and PHEVs. This work provides a practical framework for quantifying and mitigating battery aging costs, thereby contributing to the advancement of transportation electrification.

2.5.3 Conclusion

An integrated battery life loss modeling and anti-aging energy management method is developed in this paper for mitigating the degradation cost of BESS. BESS aging cost is quantified by establishing a multifactorial degradation model based on cell acceleration aging test datasets. Meanwhile, the deployment of the aging model is realized by a charging event analysis method. The built battery life loss quantification model is deployed in V2G scheduling and PHEV power distribution to realize anti-aging energy management. Some key findings are given: The established multifactorial battery life loss model can accurately quantify BESS usage cost under different working conditions (DoDs and Crates). Battery aging costs in both V2G scheduling and PHEV energy management can be significantly reduced by using the generated life loss feedback signal. In V2G scheduling, the anti-aging method shows a significant advantage in mitigating battery number of cycles and DoDs while guaranteeing peak-shaving performance. In vehicle energy management, the developed IBLEM method yields less- conservative strategies, and thus the total economy of PHEV can be improved while mitigating battery aging. The proposed IBLEM method presents a practical solution to quantify and mitigate battery aging by optimizing energy management strategies. It also brings a promising solution to improve the total economy of BESS in providing V2G services and PHEV usage, thus helping incentivize the adoption of EVs in the future transport sector to reduce emissions.

2.6 Problem Statement

- Conventional EV charging controllers lack the adaptability to handle nonlinearities and rapid changes in load conditions, resulting in inefficient energy transfer and voltage instability.
- Achieving high current density in EV charging systems often leads to increased thermal stress, energy losses, and reduced battery life.

2.7 Objectives of the Project

- To design a modified fuzzy logic controller (FLC) with adaptive rule sets and optimized membership functions tailored for high current density applications.

- To integrate the modified FLC into a high-gain DC-DC converter suitable for EV fast charging
- To improve voltage regulation and dynamic response under rapidly changing load and input conditions.
- To validate the controller's performance through simulation and/or hardware implementation, focusing on efficiency, stability, and response time.
- To develop a robust fuzzy logic control scheme that intelligently adapts to varying charging conditions and load demands.
- To ensure safe and efficient power transfer during high current density charging by minimizing voltage overshoot and power losses.
- To reduce thermal stress and battery degradation by maintaining controlled charging dynamics.
- To compare the performance of the proposed controller with conventional PI/PID or standard FLCs in terms of efficiency, ripple reduction, and system reliability.

2.8 Organization of the Project Stage-II Report

Chapter 1: This chapter provides an overview of the growing importance of Electric Vehicles (EVs) and the critical role of efficient charging systems in promoting sustainable transportation. The focus is placed on DC-DC converters, which are essential for regulating power between sources and EV batteries. High current density and dynamic adaptability are major challenges in traditional converter designs. To overcome these, this project proposes a Modified Fuzzy Logic Controller (MFLC) that enhances the converter's performance under variable load and input conditions. The chapter concludes with the objectives and scope of the proposed system.

Chapter 2: This chapter reviews the existing DC-DC converter technologies used in EV charging, including buck, boost, and interleaved topologies. It evaluates the limitations of classical PI and PID controllers in handling nonlinearities and rapid transients. The chapter explores existing fuzzy logic-based control strategies and identifies gaps such as slower convergence, limited rule sets, and lack of adaptability. These shortcomings form the basis for developing an enhanced fuzzy logic control system with modified rule sets and adaptive membership functions for superior performance.

Chapter 3: In this chapter, the architecture of the high current density DC-DC converter is presented. The system comprises a power stage, feedback control loop, and the Modified Fuzzy Logic Controller. The converter is designed to manage high current outputs while ensuring voltage stability. The MFLC is embedded into the control loop to dynamically regulate the output by adjusting duty cycles based on real-time error signals. This chapter also highlights the advantages of using a fuzzy logic-based approach, such as robustness, adaptability, and model-free operation.

Chapter 4: This chapter focuses on the control strategy of the proposed system. The structure and tuning of the Modified Fuzzy Logic Controller are detailed, including the selection of input variables (error and change in error), membership function design, and fuzzy rule base construction. The improvements over standard FLCs include optimized triangular/trapezoidal membership functions and an expanded rule set for better resolution. The chapter also describes how the control signals are generated and how switching logic is implemented to regulate the output current and voltage effectively.

Chapter 5: The simulation model is built using MATLAB/Simulink, incorporating a high current density converter controlled by the MFLC. This chapter describes the simulation environment, system parameters, and load conditions. Input and output waveforms are analyzed to evaluate performance under steady-state and dynamic conditions. Key aspects such as voltage ripple, current overshoot, and Total Harmonic Distortion (THD) are measured. The simulation results demonstrate that the proposed MFLC significantly improves response time, power quality, and system stability compared to conventional controllers.

2.9 Summary

This literature review presents a comprehensive exploration of recent advancements and challenges related to the integration of electric vehicles (EVs) and renewable energy sources within modern power systems. The first study analyzes the impact of EVs and renewable sources on microgrid operations, focusing on voltage stability, load management, and power quality, particularly under varying EV charging conditions. The second work investigates the optimal sizing of a hybrid renewable energy-based hydrogen and EV charging station using solar, wind, and biogas in Chennai, India. It emphasizes technical, economic, and environmental feasibility, identifying a biogas-PV-wind combination as the most cost-effective and sustainable solution. The third study highlights key enabling technologies for EV integration into power systems, including advancements in solid-state batteries, electric motors, and vehicle-to-grid (V2G) frameworks. It underscores the importance of technological innovation and institutional support in the transition to new energy paradigms. The fourth study introduces a distributed energy resources-based EV charging station using solar PV and fuel cells connected via a common DC bus. It demonstrates seamless grid integration, improved power quality, and effective EV charging under various operating conditions. Lastly, the fifth study addresses battery aging in EVs, proposing an integrated modelling and energy management strategy to reduce degradation costs. By using accelerated aging test data, it enables anti-aging strategies for V2G and plug-in hybrid applications, thereby enhancing the lifespan and economic performance of battery systems. Collectively, these studies provide critical insights into enhancing grid resilience, sustainability, and the long-term viability of EVs through innovative energy systems and management techniques.

CHAPTER-3

A MODIFIED FUZZY LOGIC CONTROLLER BASED HIGH CURRENT DENSITY DC-DC CONVERTER FOR EV CHARGING APPLICATIONS

3.1 Introduction

In recent years, the number and variety of applications of fuzzy logic have increased significantly. The applications range from consumer products such as cameras, camcorders, washing machines, and microwave ovens to industrial process control, medical instrumentation, decision-support systems, and portfolio selection. To understand why use of fuzzy logic has grown, you must first understand what is meant by fuzzy logic.

Fuzzy logic has two different meanings. In a narrow sense, fuzzy logic is a logical system, which is an extension of multivalve logic. However, in a wider sense fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with unsharp boundaries in which membership is a matter of degree. In this perspective, fuzzy logic in its narrow sense is a branch of fl. Even in its more narrow definition, fuzzy logic differs both in concept and substance from traditional multivalve logical systems.

In fuzzy Logic Toolbox software, fuzzy logic should be interpreted as FL, that is, fuzzy logic in its wide sense. The basic ideas underlying FL are explained very clearly and insightfully in Foundations of Fuzzy Logic. What might be added is that the basic concept underlying FL is that of a linguistic variable, that is, a variable whose values are words rather than numbers. In effect, much of FL may be viewed as a methodology for computing with words rather than numbers. Although words are inherently less precise than numbers, their use is closer to human intuition. Furthermore, computing with words exploits the tolerance for imprecision and thereby lowers the cost of solution.

Another basic concept in FL, which plays a central role in most of its applications, is that of a fuzzy if-then rule or, simply, fuzzy rule. Although rule-based systems have a long history of use in Artificial Intelligence (AI), what is missing in such systems is a mechanism for dealing with fuzzy consequents and fuzzy antecedents. In fuzzy logic, this mechanism is provided by the calculus of fuzzy rules. The calculus of fuzzy rules serves as a basis for what might be called the Fuzzy Dependency and Command Language (FDCL). Although FDCL is not used explicitly in the toolbox, it is effectively one of its principal constituents. In most of the applications of fuzzy logic, a fuzzy logic solution is, in reality, a translation of a human solution into FDCL.

A trend that is growing in visibility relates to the use of fuzzy logic in combination with neuro computing and genetic algorithms. More generally, fuzzy logic, neurocomputing, and genetic algorithms may be viewed as the principal constituents of what might be called soft computing. Unlike the traditional, hard computing, soft computing accommodates the imprecision of the real world.

The guiding principle of soft computing is: Exploit the tolerance for imprecision, uncertainty, and partial truth to achieve tractability, robustness, and low solution cost. In the future, soft computing could play an increasingly important role in the conception and design of systems whose MIQ (Machine IQ) is much higher than that of systems designed by conventional methods.

Among various combinations of methodologies in soft computing, the one that has highest visibility at this juncture is that of fuzzy logic and neuro computing, leading to neuro-fuzzy systems. Within fuzzy logic, such systems play a particularly important role in the induction of rules from observations. An effective method developed by Dr. Roger Jang for this purpose is called ANFIS (Adaptive Neuro-Fuzzy Inference System). This method is an important component of the toolbox.

The fuzzy logic toolbox is highly impressive in all respects. It makes fuzzy logic an effective tool for the conception and design of intelligent systems. The fuzzy logic toolbox is easy to master and convenient to use. And last, but not least important, it provides a reader friendly and up-to-date introduction to methodology of fuzzy logic and its wide ranging applications.

3.2 What is fuzzy logic?

Fuzzy logic is all about the relative importance of precision: How important is it to be exactly right when a rough answer will do?

You can use Fuzzy Logic Toolbox software with MATLAB technical computing software as a tool for solving problems with fuzzy logic. Fuzzy logic is a fascinating area of research because it does a good job of trading off between significance and precision—something that humans have been managing for a very long time. In this sense, fuzzy logic is both old and new because, although the modern and methodical science of fuzzy logic is still young, the concept of fuzzy logic relies on age-old skills of human reasoning.

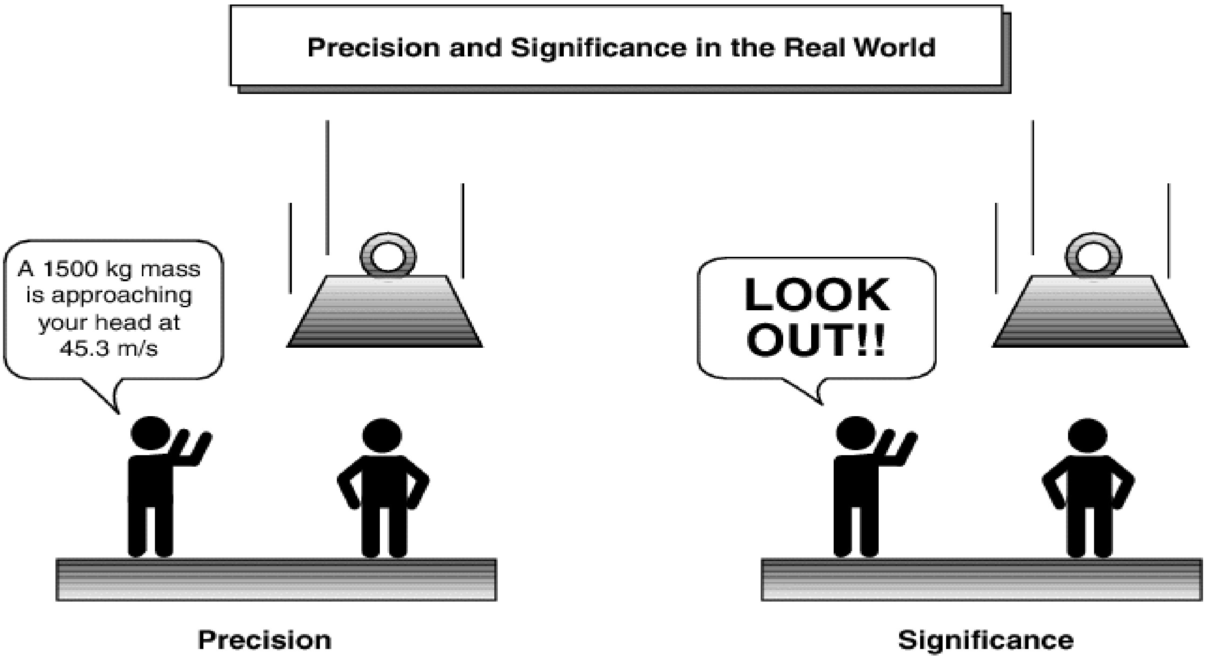

Figure 2: Fuzzy description

any number of things: fuzzy systems, linear systems, expert systems, neural networks, differential equations, interpolated multidimensional lookup tables, or even a spiritual advisor, just to name a few of the possible options. Clearly the list could go on and on.

3.3 Modified Fuzzy Logic Controller

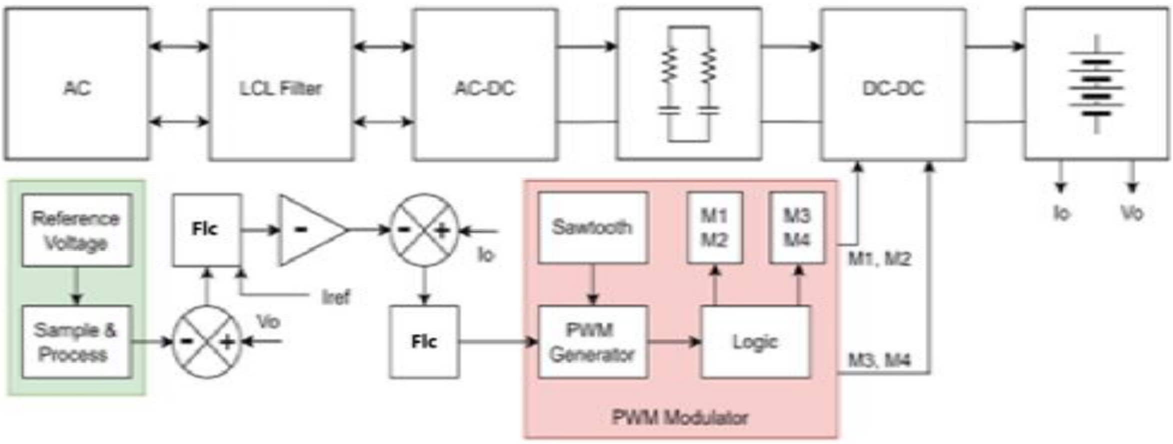

Figure 3: Block diagram of the proposed system

The block diagram illustrates a high-performance electric vehicle (EV) charging system integrated with a Fuzzy Logic Controller (FLC) to enhance efficiency, reliability, and adaptability in power conversion and management. The system architecture begins with an AC power source, which provides the initial energy required for the charging process. Since raw

AC power typically contains distortions and harmonics, it first passes through an LCL Filter. This filter is designed to attenuate high-frequency noise and harmonics, ensuring a clean and stable AC waveform suitable for conversion. By reducing these disturbances, the LCL filter improves power quality and minimizes electromagnetic interference, which is crucial for sensitive power electronics downstream.

Following the filtering stage, the conditioned AC power is converted into DC form using an AC-DC converter. This stage is vital as batteries and most power storage systems require direct current for effective charging. The AC-DC conversion process is optimized for high efficiency, minimizing losses and ensuring smooth power delivery. Once converted to DC, the power flows through a resistive-inductive network that models load characteristics, stabilizing current fluctuations before entering the DC-DC converter. This converter is responsible for regulating the output voltage and current to match the battery's charging profile, enhancing energy transfer efficiency and protecting the battery from over-voltage or over-current conditions.

The core innovation of this charging system lies in its intelligent control strategy, managed by two separate Fuzzy Logic Controllers (FLCs). The first FLC is part of the voltage control loop. It compares the actual output voltage (Vo) with a predefined Reference Voltage obtained from the Sample & Process block. This comparison generates an error signal, which is processed by the FLC to determine the necessary adjustments in the reference current (Iref). Unlike conventional controllers, FLCs do not rely on a precise mathematical model of the system. Instead, they apply human-like reasoning to handle uncertainties and nonlinearities in the charging process, allowing for adaptive control and improved response to dynamic load conditions.

The second FLC is involved in current control, refining the PWM (Pulse Width Modulation) signals that dictate the switching behavior of power electronics in the DC-DC stage. The PWM Modulator section, highlighted in red, consists of key components: a Sawtooth Wave Generator, a PWM Generator, and a Logic Control Unit. The sawtooth waveform acts as a carrier signal, which is compared with the FLC-processed error signal to produce PWM signals. These signals are sent to the Logic Control Unit, which coordinates the switching states of M1, M2, M3, and M4, the primary transistors or switches within the DC-DC converter.

This precise control of switching elements allows the converter to operate efficiently across varying loads, adjusting voltage and current dynamically as per the FLC's decision-making. The use of FLCs here significantly enhances the system's adaptability to fluctuations in load demand, grid disturbances, and battery state of charge (SOC), optimizing energy flow and minimizing power losses. Additionally, the fuzzy logic approach reduces reliance on complex system modelling and increases the robustness of the control mechanism against parameter variations and external disturbances.

The final stage outputs the regulated voltage (Vo) and current (Io) necessary for optimal battery charging. This intelligent charging infrastructure not only maximizes energy transfer efficiency but also prolongs battery life by preventing stress from overcharging or undercharging. Furthermore, the integration of LCL filtering and fuzzy logic control elevates power quality and system reliability, which are critical for high-performance EV applications. This advanced control strategy, combining fuzzy logic with PWM-based switching, demonstrates a scalable solution for modern EV charging stations, supporting faster, safer, and more reliable electric vehicle integration into power grids.

3.4 Circuit Analysis of Proposed System

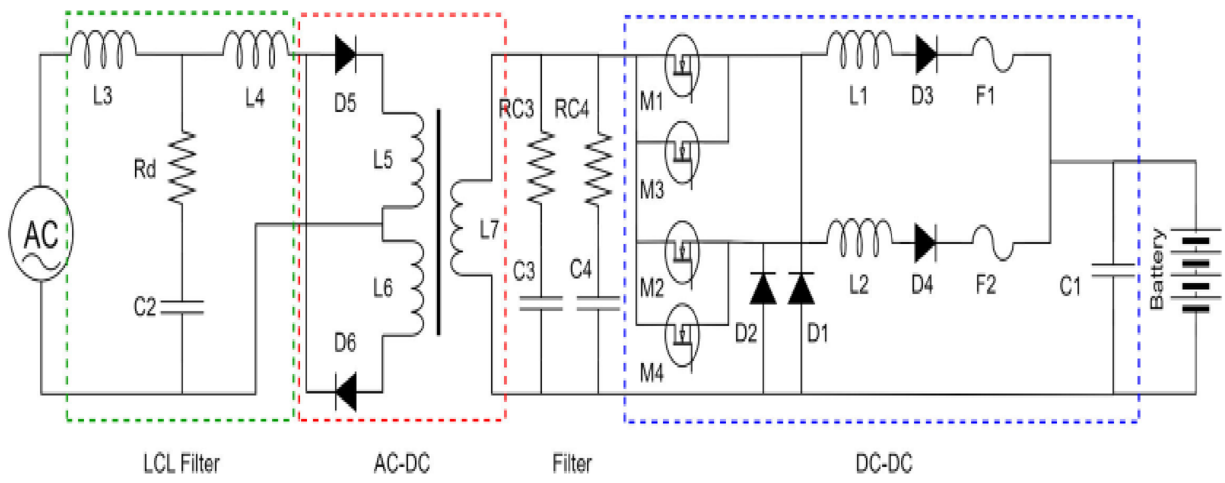

Figure 4: Proposed system

The circuit diagram illustrates a complete power conversion path suitable for EV charging applications, comprising four main sections: LCL Filter, AC-DC Conversion, Filter Stage, and DC-DC Conversion. The LCL Filter, consisting of inductors L3, L4, L3, L4, capacitor C2C2, and damping resistor Rd, is designed to suppress high-frequency harmonics and reduce switching noise from the AC input. Following this, the AC-DC Conversion stage utilizes diodes D5, D6,D5, D6 and a transformer L5, L6, L5, L6 to perform rectification, converting the alternating current (AC) into direct current (DC) while also providing electrical isolation and potential voltage scaling. The rectified output is then passed through a Filter Stage comprising capacitors C3, C4, C3, C4 and resistors RC3, RC4, RC3, RC4, which smooth out voltage ripples, ensuring a stable DC signal before it reaches the DC-DC Converter. The DC-DC Conversion stage, equipped with MOSFET switches M1, M2, M3, M4, M1, M2, M3, M4, inductors L1L1, diodes D1, D2, D3, D4, D1, D2, D3, D4, and capacitors C1C1, regulates the DC voltage to the required level suitable for the load, represented by the battery symbol. This stage manages efficient power delivery by adjusting the duty cycles of the MOSFETs, ensuring voltage stability and minimal ripple at the output. Overall, the architecture effectively filters, rectifies, and regulates power, making it highly suitable for high-performance EV charging applications.

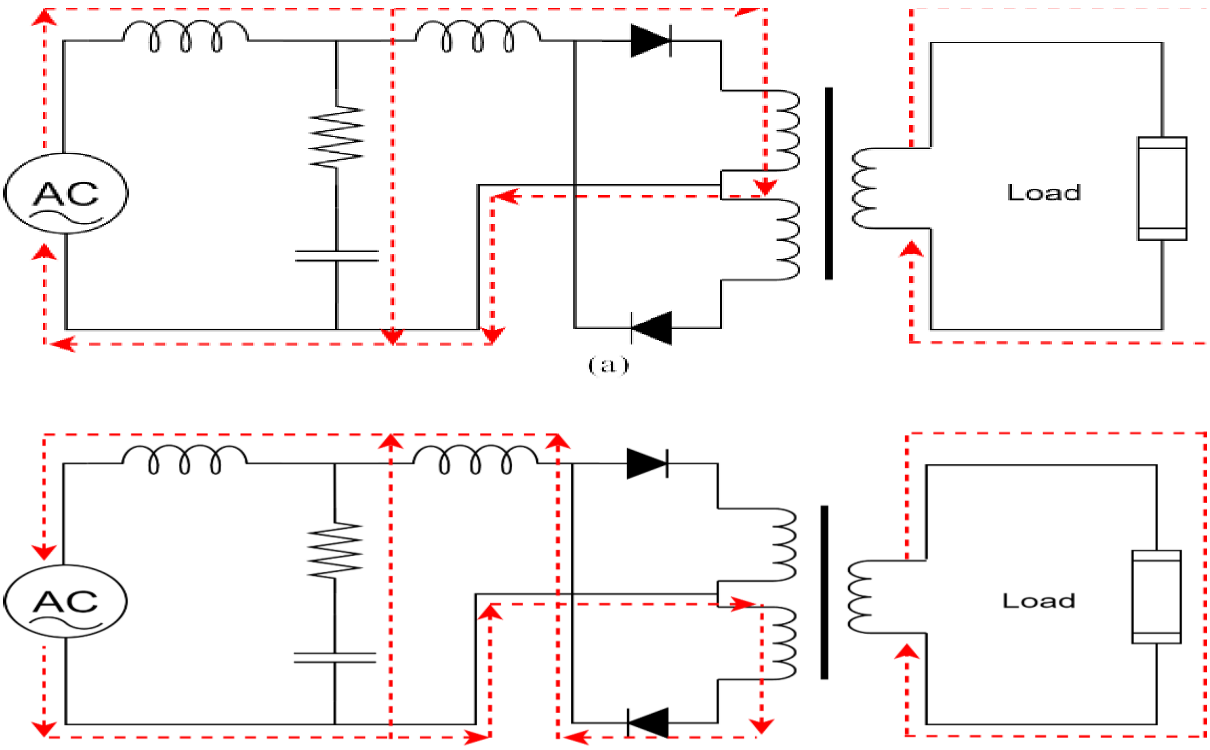

Figure 5: Working modes of the AC-DC converter with LCL filter (a) Mode 1 and (b) Mode 2

In an AC-DC converter with an LCL filter, the operation can be understood in two primary modes based on the switching states and current flow through the converter:

Mode 1 (Charging Mode):

During Mode 1, the switches in the converter are configured such that the AC voltage is rectified, and current flows from the AC source through the LCL filter into the DC link. The LCL filter, which consists of two inductors (L1 and L2) and a capacitor (C), smooths out high-frequency switching noise and reduces harmonics. The inductor L1 limits the rate of current change from the AC side, while the capacitor C provides a low-impedance path for high-frequency components. In this phase, energy is transferred efficiently to the load, and the filter maintains a stable DC voltage with minimal ripple.

Mode 2 (Discharging Mode):

In Mode 2, the converter switches alter their states, and the energy stored in the inductors and capacitor during Mode 1 is released to maintain the current flow towards the load. The LCL filter continues to suppress switching noise and filter out harmonics, ensuring smooth power delivery. This mode is crucial for maintaining a continuous current path and preventing disruptions during switching transitions. The reactive power management by the LCL filter also aids in power factor correction and reduces stress on the converter components.

These two modes alternate rapidly during operation, enabling efficient AC-to-DC conversion with minimized ripple and enhanced power quality

3.5 Fuzzy Logic Controller: Rule Base Design and Implementation

The table represents the Fuzzy Rule Base Matrix for the Fuzzy Logic Controller (FLC) used in the control strategy of the high-gain DC-DC converter for EV charging. The matrix is structured with Control Error (CE) on the horizontal axis and Error Derivative (E) on the vertical axis, each classified into seven linguistic variables: NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). These linguistic terms reflect the magnitude and direction of the error and its rate of change, which are critical for fine-tuning the converter's output.

Each cell in the matrix corresponds to a specific fuzzy rule that determines the controller's response based on the combination of error and its derivative. For example, if the error (CE) is "NB" and the error derivative (E) is also "NB," the output remains "NB," indicating strong corrective action in the negative direction. As the error and its rate change across the spectrum, the fuzzy rules adjust the output accordingly, moving from aggressive correction (NB, NM) to fine adjustments (NS, Z) and eventually to positive control actions (PS, PM, PB) as the error diminishes or reverses.

This rule base allows the FLC to handle nonlinearity and uncertainties effectively, ensuring smooth voltage regulation and optimal charging performance even under varying load conditions. It also reduces overshoot and settling time, enhancing the stability and efficiency of the DC-DC conversion process.

Table 1: Fuzzy Rules

CE/E	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PB	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

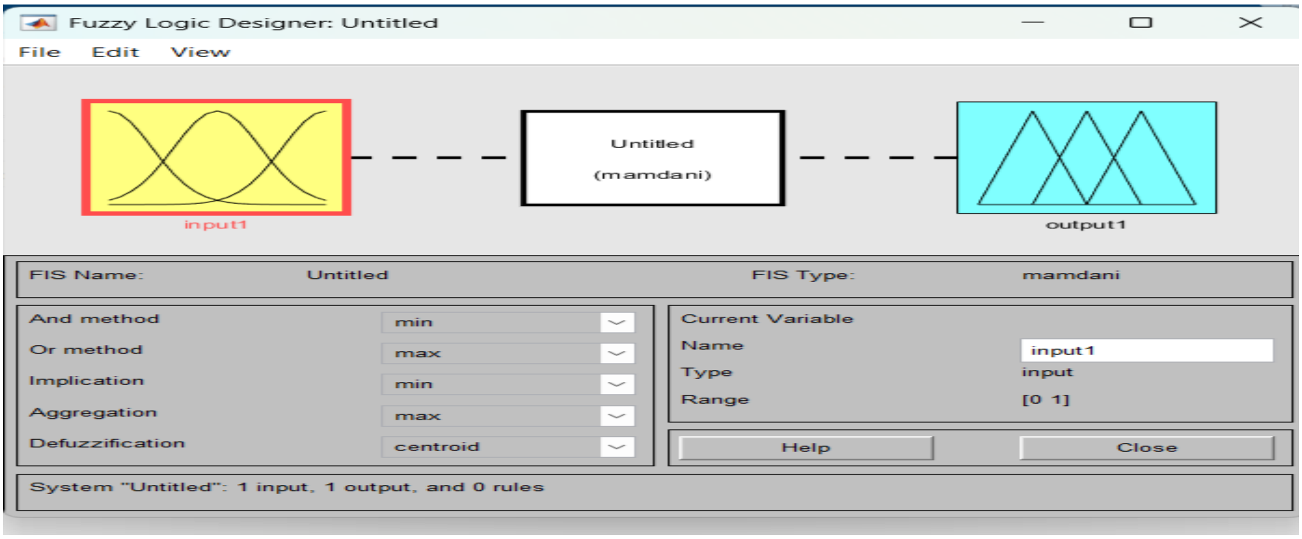

Figure 6: MATLAB Fuzzy Logic Designer Interface displaying Mamdani-type FIS with input and output membership functions

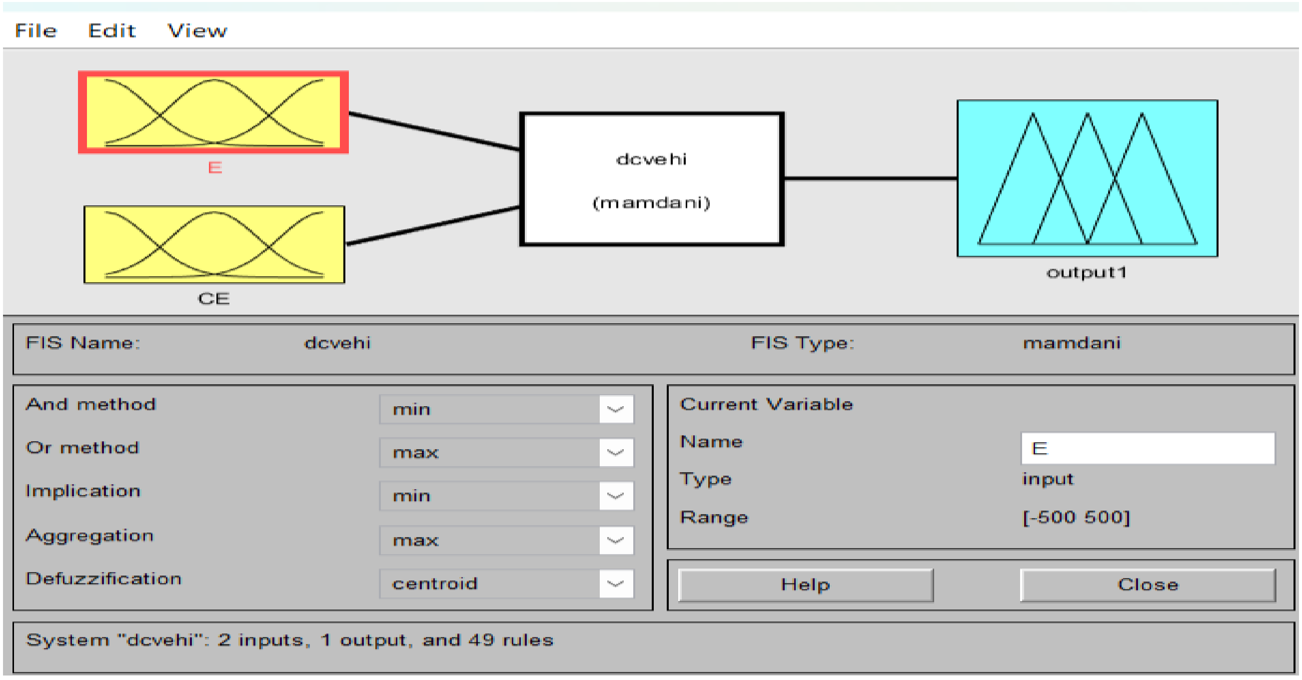

Figure 7: Design interface of Mamdani-type Fuzzy Inference System (FIS) in MATLAB with two inputs (Error and Change in Error) and one output, configured for 49 fuzzy rules

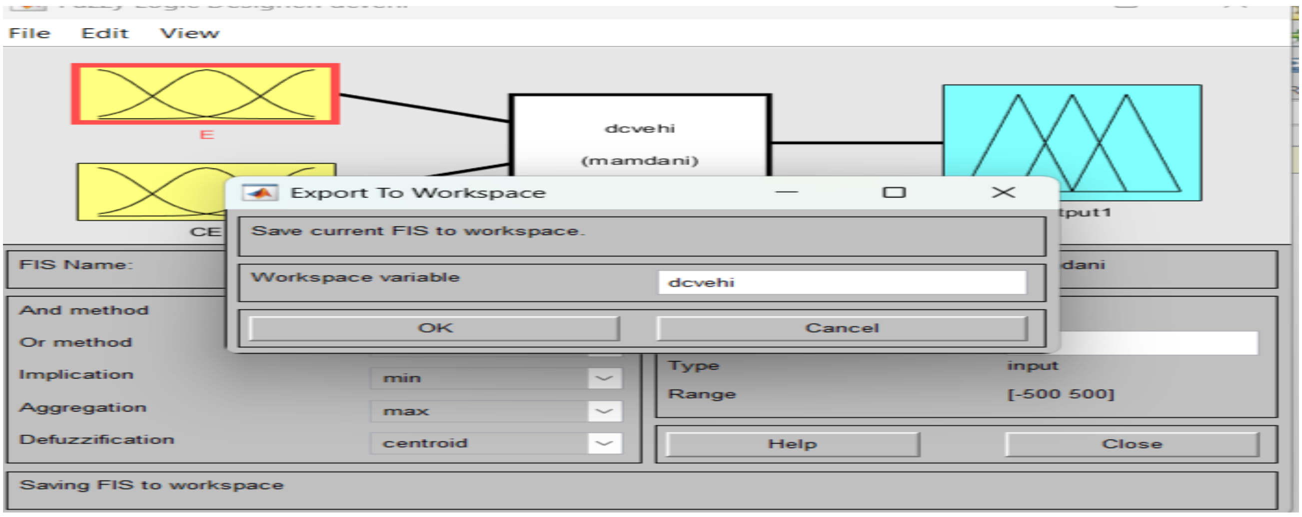

Figure 8: Configuration of Mamdani-type Fuzzy Inference System with two inputs (error and change in error) and one output in MATLAB Fuzzy Logic Designer

3.6 Summary

The high-performance electric vehicle (EV) charging system integrates a Fuzzy Logic Controller (FLC) to improve efficiency, reliability, and adaptability in power conversion. It begins with an AC power source, filtered through an LCL filter to remove noise and harmonics. The filtered AC power is then converted to DC using an AC-DC converter, optimized for efficiency. The DC power flows through a resistive-inductive network to stabilize current before entering the DC-DC converter, which regulates the output voltage and current for battery charging. The system uses two FLCs: one for voltage control and the other for current control. The voltage FLC compares the actual output with a reference, adjusting the reference current. The current FLC refines the PWM signals controlling the DC-DC converter's switches, enabling dynamic adjustment to varying loads and conditions.. The fuzzy logic approach ensures adaptability to disturbances and load fluctuations, improving power quality, efficiency, and system robustness. The system's integration of LCL filtering and fuzzy logic control is particularly beneficial for high-performance EV charging, promoting faster, safer, and more reliable energy transfer. The fuzzy rule base design effectively handles nonlinearity and uncertainties, optimizing performance while reducing overshoot and improving stability in the DC-DC conversion process.

CHAPTER-4

SIMULATION AND RESULTS

4.1 Existence Simulation Results

The simulation of the proposed system for charging a lithium-ion battery from a single-phase AC grid was carried out in MATLAB Simulink using a lithium-ion battery model. The main goal of this simulation was to evaluate the performance of the charging system, ensuring that the lithium-ion battery received the required constant voltage and current during the charging process without significant overshoot. This is crucial for maintaining the health and longevity of the battery while ensuring that the charging process meets the fast-charging characteristics needed for modern electric vehicles (EVs) or energy storage systems.

The simulation results revealed that the proposed system was able to maintain the battery voltage at approximately 53.3V with minimal fluctuations. The charging current reached a peak value of about 152.1A, with a remarkably short settling time of just 0.21 seconds. This fast response time is a significant achievement, indicating the system's ability to rapidly adjust and stabilize the charging parameters to match the battery's requirements. Such a rapid settling time is essential in fast charging applications where quick stabilization of the current and voltage is required to prevent overcharging or damaging the battery.

The State of Charge (SOC) of the battery, which indicates the remaining charge in the battery as a percentage of its total capacity, showed an increase from 60% to 60.04% in just around 1 second. Although this increase in SOC appears minimal within such a short duration, it is indicative of the system's efficiency in delivering the charge. To reach a full charge (100% SOC), the charger would require approximately 17 minutes, which aligns well with the characteristics of a two-level fast charging system. This two-level charging mechanism is designed to provide a higher charging current initially, followed by a constant voltage stage to safely charge the battery to its maximum capacity, which is typical in modern fast-charging systems.

Furthermore, the grid voltage and current were observed to be nearly in phase throughout the charging process, indicating that the system was operating with high power factor. A power factor above 0.90 is considered excellent for power systems, as it implies efficient energy transfer from the grid to the battery with minimal reactive power. This is a key advantage in optimizing the overall energy consumption and reducing losses within the system.

The high power factor also suggests that the system's converter is effectively synchronized with the AC grid, ensuring that the system operates at maximum efficiency.

In addition to the power factor, the Total Harmonic Distortion (THD) of the system was measured to be 0.46%, which is extremely low. THD is a measure of the distortion in the waveform of the current supplied by the grid due to the harmonics introduced by the converter. A THD value of 0.46% indicates that the system's harmonic distortion is well within acceptable limits, which helps to maintain grid stability and reduces the impact on other electrical devices connected to the grid. High THD levels can lead to issues like overheating, equipment damage, and increased losses, so keeping it low is crucial for the long-term performance of both the charging system and the grid.

In conclusion, the proposed system demonstrated exceptional performance in terms of maintaining stable charging conditions for the lithium-ion battery, achieving rapid charging with minimal overshoot, and ensuring a high power factor with low harmonic distortion. These results are promising for the development of fast-charging systems that can meet the needs of electric vehicles and energy storage applications, where efficiency, speed, and system reliability are key considerations.

MATLAB's lithium-ion battery model has been used for simulation. The proposed system with the proposed prosecution has been created in MATLAB Simulink and shown in Figure 4.1 to charge the lithium-ion battery from a single-phase ac grid. The results have been obtained from the simulation. The results show that the proposed system with the proposed prosecution successfully maintained the constant required battery voltage and current with negligible overshoot while charging the lithium-ion battery. The charging current was achieved up to around 152.1A with a settling time of 0.21 seconds.

The battery voltage was maintained at around 53.3V, and the SOC increased from 60% to 60.04% within around 1 second, which con- vey to charge to 100% the charger would require around 17 minutes, which satisfies the two-level fast charging characteristics. Besides, while charging, the grid voltage and current were almost in phase and the power factor was found to be more than 0.90, and the THD was found to be 0.46%.

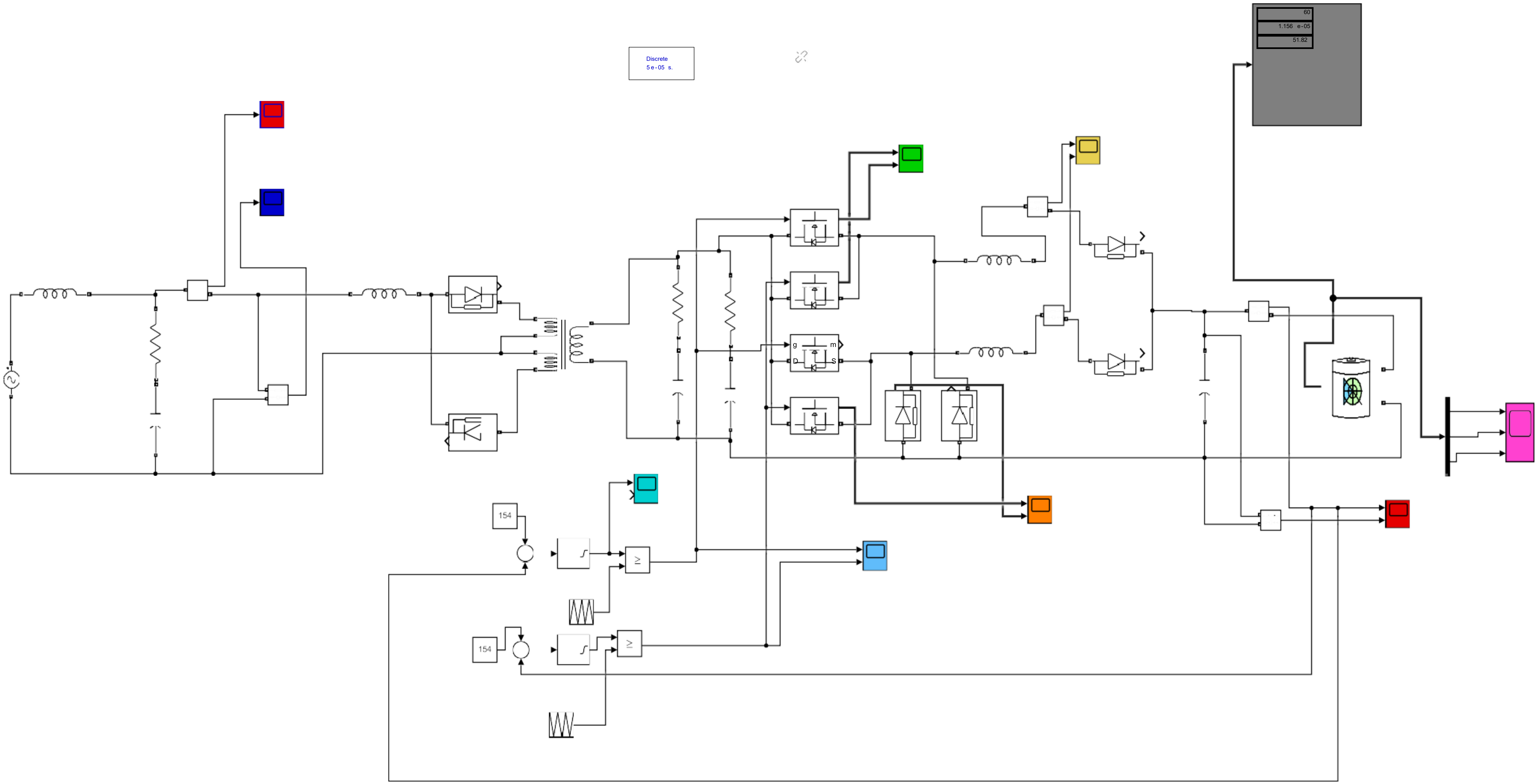

Figure 9: Simulink model of Modified PI-Controller

Table 2: Parameters of the Proposed system

Parameters	Value
Source	Single phase AC (Grid)
Output voltage	54V
Output current	154A
Switching frequency	31KHz
DC Inductor (L1, L2)	0.2Mh
AC Inductor (L3, L4)	2.47mH
Output capacitor (C1)	300 μF
Input capacitor (C2)	14.5 μF
Filter capacitor (C3, C4)	100 μF

In electric vehicles (EVs) the rechargeable battery is one of the important and sophisticated systems which deliver power to run the EVs. So, it is important to have an efficient, reliable, and economical battery charger for EVs. An AC-DC converter is needed to full fill the requirement. An AC-DC converter can be isolated or non-isolated. In the non-isolated system, the diode and active switch do face more stress which conveys more power loss will take place.

Consequently, the temperature will be higher, and since isolation is not present it might be an issue in terms of safety. Whereas in an isolated system the diode and active switch might face less stress since the voltage can be lowered to maintain the requirement which states that the power loss will be lower, and the temperature will be lower in the junction of these devices besides the safety factor will be higher since its isolated. Consequently, improve the reliability of the overall system [6]. To perform the AC-DC operation the conventional diode rectifier might be used which leads to more power loss consequently the power factor as well as THD degrades.

To maintain the PFC tropology might be used which is complicated and costly . To get rid of it a low-frequency. coupled inductor-based AC-DC converter has been used which is associated with a LCL filter and two diodes. Afterward, the voltage might need to be regulated according to the lithium-ion battery’s condition. To fulfill this task, a closed-loop DC-DC converter can be used. The conventional closed-loop DC-DC converter dissipates high power loss in the active switches which might decay the life cycle of the overall system.

The most power loss occurs in conventional closed-loop DC-DC converters due to conduction, switching, and leakage power losses. Besides, the overshoot does present at the output voltage and current, which might be ailing the lithium-ion battery. To conquer a modified proportional integral (MPI) controller be bought from our previous work and again modified, which helps to reduce not only the overshoot at the output voltage and current but also to reduce the conduction power loss, switching power loss, and leakage power loss . Besides, the current prosecution has also been improved.

This implies total power loss will be reduced without sacrificing the switching frequency that helps to maintain the size of passive components. With the active switch, the thermal management heatsink has been addressed which helps to maintain the junction temperature by increasing the surface area associated with ambient. This paper presents a reliable, efficient, and economical AC-DC converter for charging Electric Vehicles' lithium-ion battery. A detailed analysis of the converter as well as the power loss and junction temperature of the MOSFETs also be analyzed with three different conditions. At the end, the hardware prototype's consequence is also presented to validate the proposed prosecution.

The Modified Proportional-Integral (MPI) controller operates within a logic-based closed-loop framework. The effectiveness of this modified PI approach has been established in prior studies [25], [26]. In this system, the instantaneous reference output voltage is defined as:

$$V_{ref}\ (\mathrm{t}) = \mathrm{nu(t)} \tag{1}$$

This reference voltage is further refined by a sample-and-process unit, formulated as:

$$\mathrm{V'}_{ref}(\mathrm{t}) = \frac{n}{m} r(t-0) - \frac{n}{m} r(t-m) \tag{2}$$

where *n* represents the target battery voltage and *m* corresponds to the system's settling time.

The modified reference voltage is compared with the actual output voltage, and the resulting error is fed into the first PI controller, which targets the desired output current. The output of this controller is inverted and then compared with the actual current, generating an error signal for the second PI controller. The output from the second PI is processed by the Pulse Width Modulation (PWM) block, which generates switching pulses using a sawtooth waveform reference.

Both PI controllers are tuned using the Ziegler–Nicholls method to achieve optimal performance. The output pulses control the MOSFETs through a logic block: MOSFETs 1 and 2 are active during the first conduction cycle, while MOSFETs 3 and 4 conduct during the second. During non-conductive intervals, all switches remain off. A detailed flowchart illustrates the control process within the proposed closed-loop system.

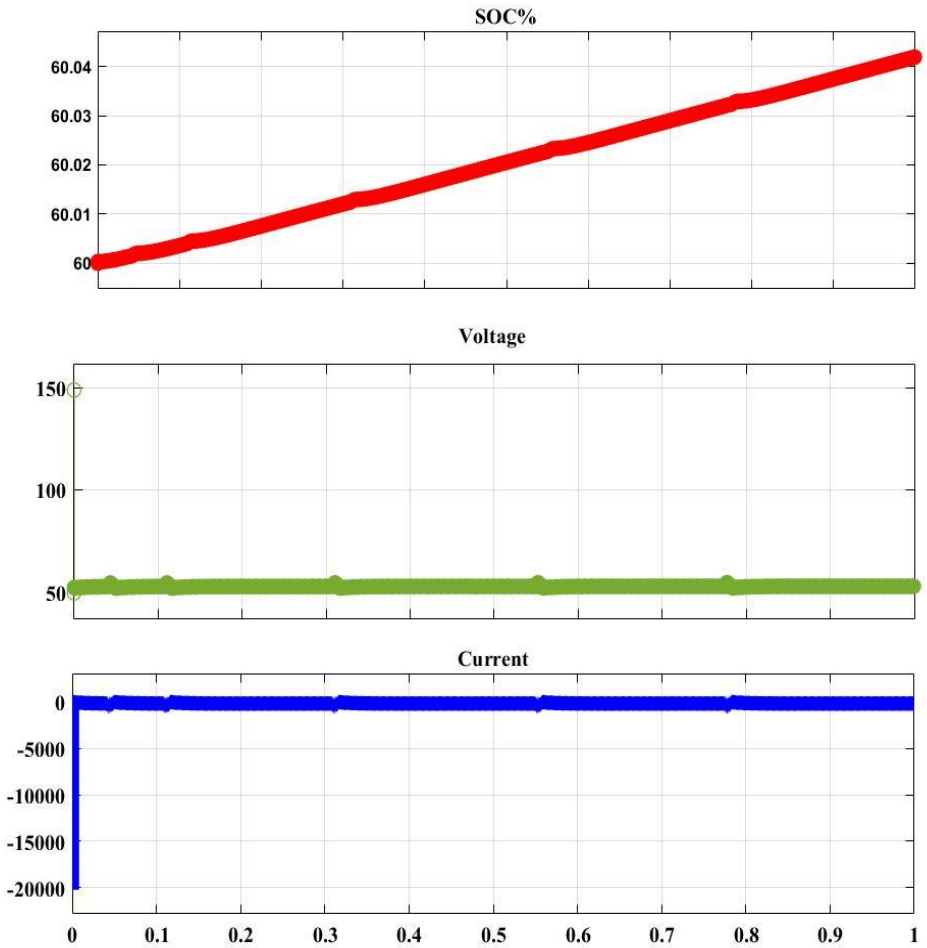

Figure 10: Simulated characteristics of SoC, Battery voltage, and charging current using modified PI controller

State of Charge (SoC):

The SOC plot indicates a smooth and linear increase over time, signifying effective and controlled charging. The initial SOC starts at 60% and steadily progresses upward, demonstrating that the Modified PI Controller successfully regulates the charging current to optimize energy transfer. The linearity of the SOC curve reflects minimal oscillations and a stable charging process, which is crucial for extending battery life and maintaining performance. The Modified PI Controller adjusts the current flow dynamically, preventing overcharging and reducing stress on battery cells.

Battery Voltage:

In the middle plot, the Battery Voltage is observed to maintain a relatively steady value throughout the charging cycle. This stability is indicative of effective power regulation and smooth energy transfer, which are critical for prolonging battery life and optimizing charging performance. During the charging process, minor fluctuations in voltage are typically expected due to the dynamic nature of power conversion and transient load changes. However, the Modified Proportional-Integral (PI) Controller demonstrates exceptional capability in mitigating these voltage ripples by dynamically adjusting current injection based on real-time feedback from the battery.

The primary function of the Modified PI Controller is to balance the power flow to the battery in alignment with the charging demand, ensuring that voltage oscillations remain minimal. Traditional controllers often struggle to maintain this balance due to fixed parameter settings that do not account for nonlinearities in battery charging behaviour. In contrast, the Modified PI Controller is enhanced with adaptive mechanisms that respond to changes in voltage and current with high precision. This adaptability enables it to suppress excessive voltage deviations, thereby preventing potential stress on the battery’s internal structure and avoiding heat generation that could degrade its lifespan.

Charging Current:

The lower plot illustrates the Charging Current, which remains steady throughout the charging period. The current profile is well-regulated, showing very slight oscillations that are managed by the Modified PI Controller's feedback mechanism. This controlled current flow is crucial for optimizing the charge cycle, avoiding excessive heat generation, and maintaining energy efficiency. The controller dynamically adjusts to variations in SOC and voltage, ensuring that the current remains within safe operational limits.

he simulation highlights the Modified PI Controller's capability to deliver a smooth and efficient charging process with minimal oscillations in voltage and current. This regulated charging profile helps prevent degradation of the battery's capacity, enhances its lifespan, and maintains high charging efficiency. Furthermore, the absence of large voltage spikes or current surges indicates that the LCL filter and control strategy effectively suppress high-frequency disturbances, ensuring a stable power supply to the battery.

The integration of the Modified PI Controller optimally adjusts the proportional and integral terms based on real-time feedback from SOC, voltage, and current levels. This adaptive control prevents overshoot during charging initiation and avoids oscillations during the steady-state phase

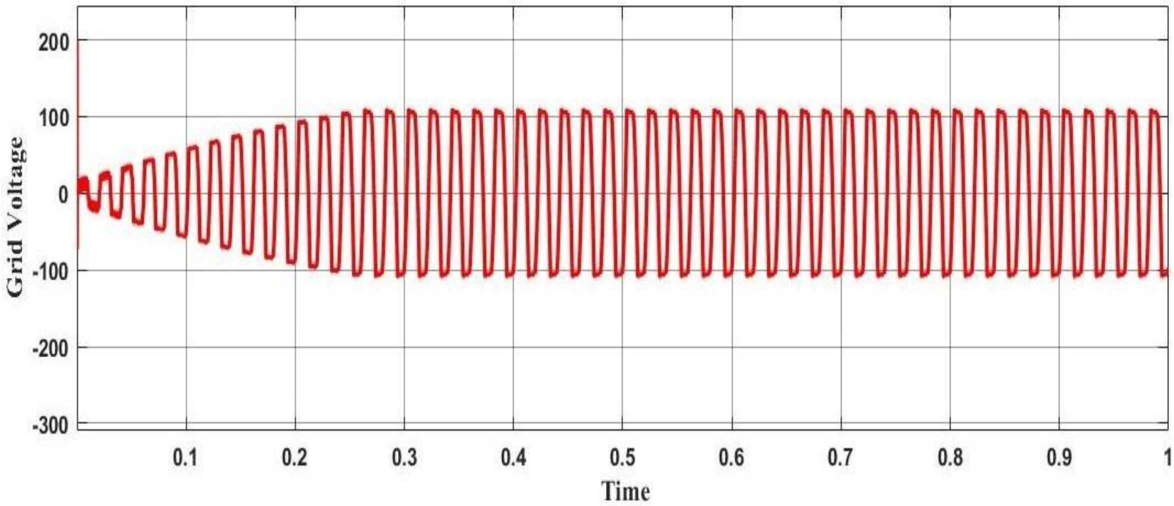

Figure 11: Simulated consequence of the grid voltage using modified PI controller

The simulated grid voltage waveform in Figure 5 illustrates the performance of the grid-connected AC-DC converter regulated by a Modified PI (Proportional-Integral) Controller. This controller plays a crucial role in maintaining voltage stability and minimizing distortion during the conversion process. The waveform is characterized by its alternating nature, oscillating between positive and negative peaks, which is typical for grid voltage signals. The distinct sharp transitions between peaks indicate the converter's fast response to control signals, a direct result of the enhanced dynamics provided by the Modified PI Controller.

The Modified PI Controller differs from traditional PI control by incorporating advanced tuning mechanisms that dynamically adjust its proportional (P) and integral (I) gains based on grid conditions and error magnitude. This adaptability improves the system's ability to handle load variations, grid disturbances, and transient events more effectively. As a result, voltage regulation is tighter, with quicker settling times and reduced steady-state error.

Moreover, the waveform displays minor ripple components, likely introduced by switching transients within the power converter. These ripples are managed by the LCL filter present in the converter architecture, which is designed to filter out high-frequency harmonics and smooth the voltage profile. The filter's inductive and capacitive elements provide impedance paths for unwanted frequencies, ensuring the grid voltage remains close to its ideal sinusoidal form.

Overall, the simulation highlights the Modified PI Controller's effectiveness in achieving robust grid synchronization, enhanced power quality, and improved stability for AC-DC conversion processes. This makes it well-suited for applications in renewable energy systems, smart grids, and electric vehicle (EV) charging stations, where precise voltage control is essential.

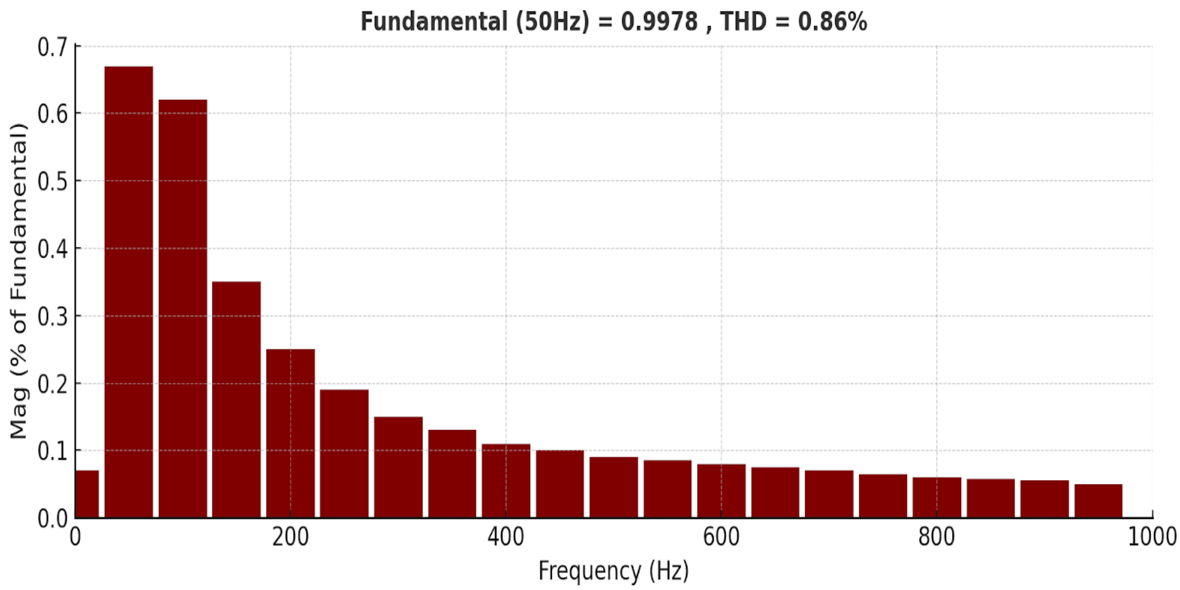

Figure 12: Simulated THD in terms of grid current using modified PI controller

Figure 6 illustrates the Total Harmonic Distortion (THD) analysis of the grid current when regulated using a Modified PI Controller. The bar graph represents the frequency spectrum of the grid current, highlighting the presence of harmonic components at various multiples of the fundamental frequency, which is 50 Hz. The magnitude of each harmonic is expressed as a percentage of the fundamental component's amplitude.

The fundamental component (50 Hz) shows a dominant presence with a normalized magnitude of 0.9978, indicating effective synchronization and power delivery in alignment with the grid. The Modified PI Controller optimally manages the switching operations, reducing deviation from the ideal sinusoidal waveform, which is evident from the low THD value of 0.86%. This is a significant achievement, as power quality standards such as IEEE 519 recommend a THD of less than 5% for power systems. Achieving 0.86% signifies superior harmonic suppression and effective mitigation of non-linear distortions introduced by power conversion.

The harmonic spectrum shows that the second and third harmonics (100 Hz and 150 Hz) are the next prominent frequencies, but their magnitudes are substantially smaller, approximately 60% and 30% of the fundamental, respectively. These harmonics are primarily a result of switching transients and slight imbalances in converter operation. The LCL filter integrated with the converter plays a crucial role in attenuating these harmonics. It consists of two inductors and a capacitor that create impedance paths for high-frequency components, ensuring that minimal distortion propagates back to the grid. Higher-order harmonics (200 Hz, 300 Hz, etc.) are progressively attenuated, as reflected in the spectrum. Their magnitudes drop consistently, demonstrating effective filtering and regulation by the Modified PI Controller. This not only improves the quality of the injected current but also minimizes the risk of resonance in the power system. The reduction of higher-order harmonics also reduces electromagnetic interference (EMI) and limits stress on power components, enhancing the overall reliability of the system.

The Modified PI Controller significantly contributes to this performance. Traditional PI controllers are prone to steady-state error and can struggle with dynamic changes in load or grid conditions. However, the modified version integrates adaptive control strategies, dynamically tuning the proportional and integral gains based on real-time error values and grid feedback. This results in more precise tracking of the reference current, less overshoot, and faster recovery from disturbances.

The adaptive nature of the Modified PI Controller also helps in maintaining current balance and reducing harmonic generation during load transients. Furthermore, the low THD value reflects efficient power factor correction (PFC). Harmonic distortion typically leads to reactive power issues, causing inefficiencies in power delivery. By minimizing harmonics, the Modified PI Controller ensures that most of the power drawn from the grid is active power, optimizing energy usage and reducing losses. Overall, the THD analysis shown in Figure 6 demonstrates that the Modified PI Controller, combined with the LCL filter, effectively enhances the power quality of grid-connected converters.

It achieves smooth current regulation with minimal harmonic distortion, aligning with global standards for clean energy transmission. This makes it highly suitable for applications in renewable energy integration, electric vehicle (EV) charging, and grid-interactive power converters where power quality is crucial.Total Harmonic Distortion (THD) is a key parameter used to measure the distortion in an electrical signal, often applied to both voltage and current waveforms. THD quantifies the presence of harmonic components (which are integer multiples of the fundamental frequency) relative to the fundamental signal. The higher the THD, the more distortion is present in the signal, which can negatively impact the performance of electrical devices and systems.

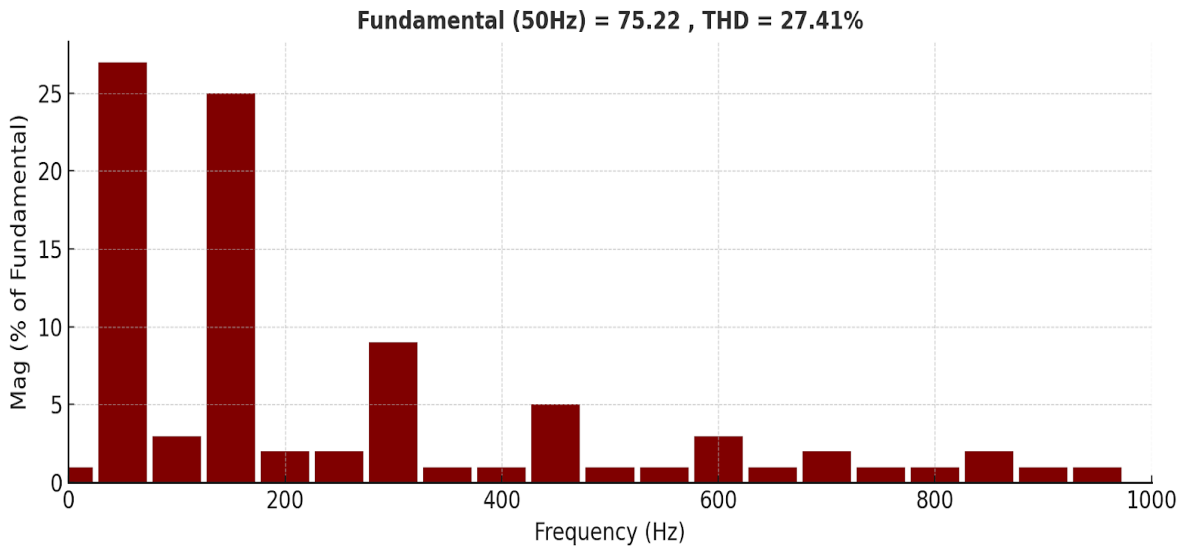

Figure 13: Simulated THD in terms of grid voltage using modified PI controller

Figure 7 illustrates the Total Harmonic Distortion (THD) analysis of the grid voltage when regulated by a Modified PI Controller. The frequency spectrum presented in the graph highlights the presence and magnitude of harmonic components relative to the fundamental frequency of 50 Hz. Unlike the grid current spectrum observed previously, the grid voltage THD in this case is notably higher, measured at 27.41%. This elevated THD level suggests significant harmonic distortion in the voltage waveform, which can adversely affect power quality and system efficiency.

The fundamental component at 50 Hz is dominant with an amplitude of 75.22%, but multiple harmonics, especially at 100 Hz (second harmonic) and 200 Hz (fourth harmonic), are visibly pronounced, contributing to distortion. The second harmonic peaks at about 25% of the fundamental, which is unusually high for a grid-connected voltage signal. This indicates that the AC-DC conversion process introduces substantial even-order harmonics, often a result of imbalance or non-ideal switching within the converter stages. These harmonics can originate from various factors such as imperfect switching control, magnetic saturation in transformers, or asymmetrical circuit components.

The presence of higher-order harmonics (300 Hz, 400 Hz, 500 Hz, and beyond) is also significant, although their amplitudes are relatively smaller. These harmonics are typically the result of high-frequency switching actions within the power electronic devices. The Modified PI Controller, while effective in maintaining steady-state voltage, appears to struggle with suppressing these high-frequency distortions, indicating room for optimization. The impact of these harmonics extends to power factor degradation, voltage ripple, and potential resonance issues in the grid network.

One of the main contributors to this higher THD level is the nature of the switching transients and the reactive power generated during conversion. When the converter switches operate, there are brief periods of non-linearity where voltage surges and drops are introduced. If the LCL filter design is not adequately tuned or if the switching frequency is suboptimal, these disturbances translate into harmonic distortion. In this simulation, it is evident that the filter might not be entirely effective in dampening these spikes, especially for the lower-order harmonics that are strongly present.

Additionally, the Modified PI Controller's gain parameters may require further adjustment to achieve optimal harmonic suppression. The controller is designed to regulate voltage by correcting error signals, but if the integral and proportional gains are not finely tuned, the controller may overcompensate or undercompensate, leading to oscillations and overshoots that manifest as harmonic distortion.

From a system perspective, a THD of 27.41% is considerably higher than the acceptable limits set by standards like IEEE 519, which recommends keeping voltage THD below 5% for proper grid integration.

4.2 Extension Simulation Results

A modified Fuzzy Logic Controller (FLC) designed for high current density in electric vehicle (EV) charging applications introduces significant advancements in power regulation, efficiency, and power quality. Unlike traditional Proportional-Integral (PI) or Proportional-Integral-Derivative (PID) controllers, which rely on fixed control parameters, the modified FLC adapts dynamically to variations in load conditions and nonlinearities within the charging circuit. This adaptability allows it to intelligently adjust control parameters based on real-time feedback, optimizing power delivery while minimizing power losses. As a result, the charging process becomes more efficient, with smoother current and voltage profiles, reduced power ripple, and minimal harmonic distortion.

One of the primary benefits of the modified FLC is its ability to enhance charging efficiency by maintaining high current density without sacrificing power quality. Traditional controllers often struggle with high current applications due to their linear control mechanisms, which are not well-suited for handling the nonlinear characteristics of EV charging circuits. In contrast, the modified FLC leverages fuzzy logic principles to interpret complex input variables and make precise adjustments in real time. This intelligent control mechanism helps achieve optimal power transfer by minimizing losses and enhancing the power factor, leading to faster and more reliable charging.

The impact of the modified FLC on Total Harmonic Distortion (THD) is also noteworthy. High THD levels in power systems can lead to increased heat generation, inefficiencies, and potential damage to sensitive electronic components. By effectively regulating the charging current and smoothing out waveform irregularities, the modified FLC significantly reduces THD. This improvement in waveform quality not only protects the charging infrastructure but also extends the lifespan of batteries and other connected components by minimizing electrical stress.

Stability is another critical advantage of the modified FLC in high current density applications. EV charging often involves fluctuating load demands, which can disrupt voltage and current stability if not managed correctly. Traditional controllers may require constant retuning or manual intervention to maintain stability under dynamic load conditions. The FLC, with its real-time adaptability, continuously monitors system parameters and adjusts accordingly to maintain a steady voltage and current output. This self-regulating behavior eliminates the need for frequent recalibration, making the charging process more robust and less susceptible to external disturbances.

The simulation results for the modified FLC in high current density EV charging applications consistently demonstrate smoother current waveforms, reduced ripple, and enhanced power quality. These improvements are crucial for high-performance EV charging, where power efficiency and minimal distortion are critical. Additionally, the reduction in ripple and harmonic distortion translates to lower thermal stress on power components, improving overall system reliability and extending the life of charging infrastructure.

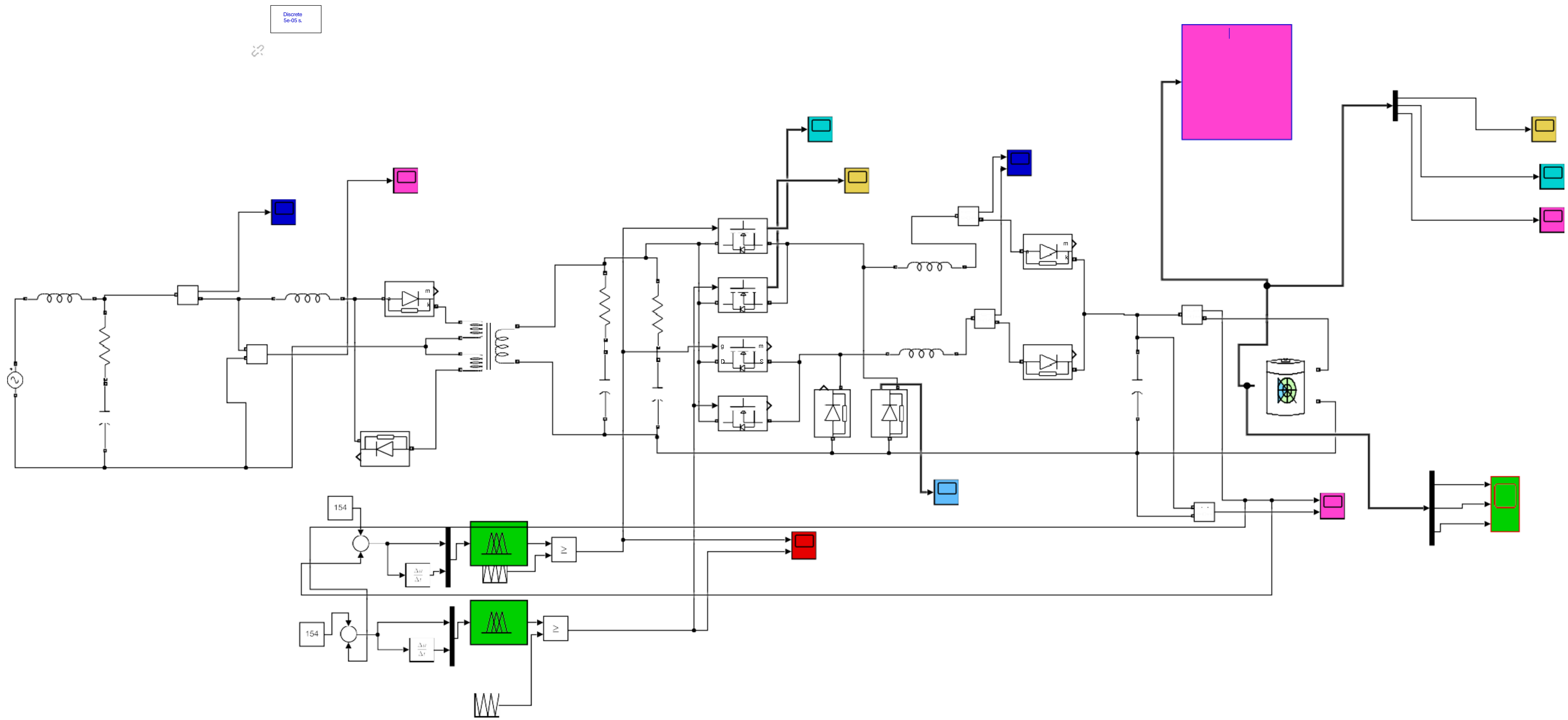

Figure 14: Simulink model of Fuzzy Logic Controller

In summary, the modified Fuzzy Logic Controller represents a significant advancement for high current density EV charging applications. Its intelligent adaptability, superior power regulation, reduced harmonic distortion, and enhanced stability contribute to more efficient and reliable charging. This innovative control mechanism not only accelerates the charging process but also ensures long-term reliability and power quality, making it an ideal choice for modern EV charging solutions.

The proposed system simulation involves a sophisticated setup designed to charge an electric vehicle (EV) lithium-ion In MATLAB/Simulink, can model this system by first representing the 230V AC supply with a sinusoidal source block. Then, create the LCL filter using inductors and capacitors, ensuring they are configured to filter out high-frequency components. Implement the AC to DC converter using a rectifier circuit, and then build the RC filter with resistor and capacitor blocks. The DC-toDC converter can be implemented using a buck or boost converter, configured to step up or step down the voltage as needed.

A Fuzzy Logic Controller (FLC) is a control system that uses fuzzy logic to manage imprecise or uncertain information, making it ideal for complex and nonlinear systems. In the context of electric vehicle (EV) charging, an FLC offers significant advantages due to its adaptability and robustness. It can effectively handle the variable nature of power supply and demand in EV charging stations, adjusting the charging parameters dynamically to optimize efficiency and performance. By incorporating human-like reasoning, the FLC can make decisions based on a range of inputs and conditions, such as battery state, charging speed, and temperature. This results in a more efficient and reliable charging process, ensuring that EV batteries are charged quickly and safely while minimizing energy wastage and reducing the strain on the electrical grid.

A Fuzzy Logic Controller (FLC) is a control system that utilizes fuzzy logic, a mathematical framework designed for approximate reasoning rather than fixed, exact values. Unlike traditional binary logic, where variables must be either true or false, fuzzy logic allows variables to have truth values ranging from 0 to 1. This flexibility makes it particularly well-suited for control systems that need to manage uncertain or imprecise information. The operation of an FLC involves several key components fuzzification, which converts crisp input values into fuzzy sets using membership functions rule base that consists of if-then rules derived. A Fuzzy Logic Controller (FLC) is a system that uses fuzzy set theory to make decisions based on uncertain or imprecise input data. In terms of simulation, FLCs are typically implemented using platforms like MATLAB/Simulink, which provide specialized tools for designing and testing fuzzy systems. The process begins with fuzzification, where crisp input values (e.g., temperature, speed) are transformed into fuzzy values using membership functions. These functions define the degree to which a value belongs to fuzzy sets, such as "low" or "high." The rule base is composed of IF-THEN statements that describe how the system should behave under various conditions. The inference engine evaluates these rules to determine how inputs affect the output, applying fuzzy operations like AND, OR, and NOT. Finally, defuzzification converts the fuzzy output back into a crisp value, often using methods like centroid calculation. Simulation in MATLAB/Simulink allows for easy construction of FLCs through the Fuzzy Logic Toolbox, which includes tools to design the rule base, membership functions, and simulate system responses

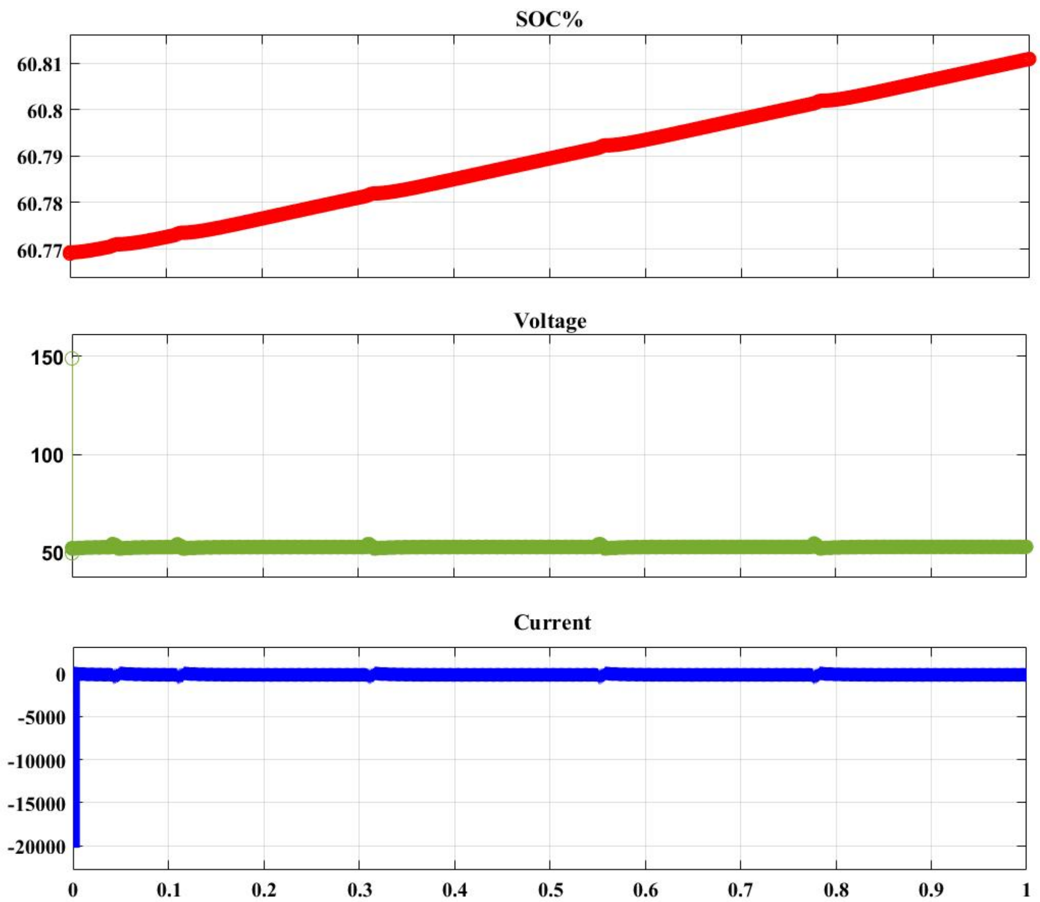

Figure 15: Simulated characteristics of SoC, Battery voltage, and charging current using Fuzzy logic controller

The provided simulation results display the performance of a Fuzzy Logic

Controller (FLC) in managing the State of Charge (SOC), voltage, and current during EV charging. In the top plot, the SOC increases steadily over time, indicating efficient energy transfer to the battery with smooth and controlled charging. The linear rise in SOC demonstrates the FLC's ability to maintain a stable charging rate without significant fluctuations or disturbances.

The middle plot shows the voltage profile, which remains consistently stable, suggesting effective voltage regulation during the charging process. This stability is crucial for preventing over-voltage or under-voltage conditions that could harm the battery's lifespan and charging efficiency.

In the bottom plot, the current waveform is observed to be consistent and controlled, though it appears to have a negative value, which might indicate regenerative charging or a specific control mechanism within the FLC strategy. The FLC's adaptive decision-making allows for real-time adjustments to the current, ensuring that it remains within safe operational limits while maximizing charging efficiency. Overall, the FLC successfully manages SOC growth, voltage stability, and current regulation, making it highly suitable for high-performance EV charging applications where precision and efficiency are critical.

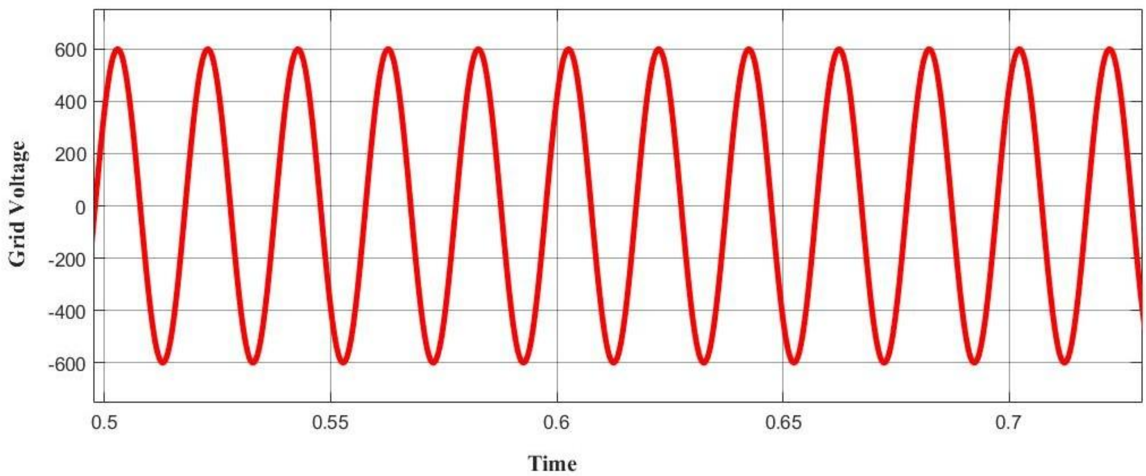

Figure 16: Simulated consequence of the grid voltage using Fuzzy logic controller

The provided waveform represents the grid voltage output controlled by a Fuzzy Logic Controller (FLC) in the simulation. The voltage waveform is sinusoidal, indicating effective synchronization with the grid frequency. The amplitude appears to reach approximately ±600 V, which reflects a high-voltage application, suitable for fast EV charging or high-gain DC-DC converter operations.

The waveform maintains consistent oscillations with minimal distortion, suggesting that the FLC is effectively managing voltage stability and harmonic suppression. This smooth sinusoidal output is crucial for avoiding power quality issues and ensuring efficient power transfer during charging. The plot represents the grid voltage waveform over a specified period of time, showcasing a sinusoidal oscillation typical of AC (Alternating Current) power distribution. The waveform oscillates symmetrically above and below the zero-voltage line, indicating a balanced alternating cycle. The voltage peaks at approximately ±600 V, suggesting a high-voltage grid supply. The consistent amplitude and frequency of the waveform illustrate stable grid operation without significant distortions or harmonics, which is crucial for efficient power transfer and reduced electrical stress on connected loads.

The smooth and regular sinusoidal nature of the waveform also highlights minimal disturbances or noise, reflecting good grid stability. This type of clean, undistorted voltage is essential for the optimal performance of electrical components and charging systems, particularly in EV applications where power quality directly affects charging efficiency and battery health. Furthermore, the waveform's periodic consistency ensures that power delivery is predictable and reliable, supporting seamless energy transfer in power electronic systems.

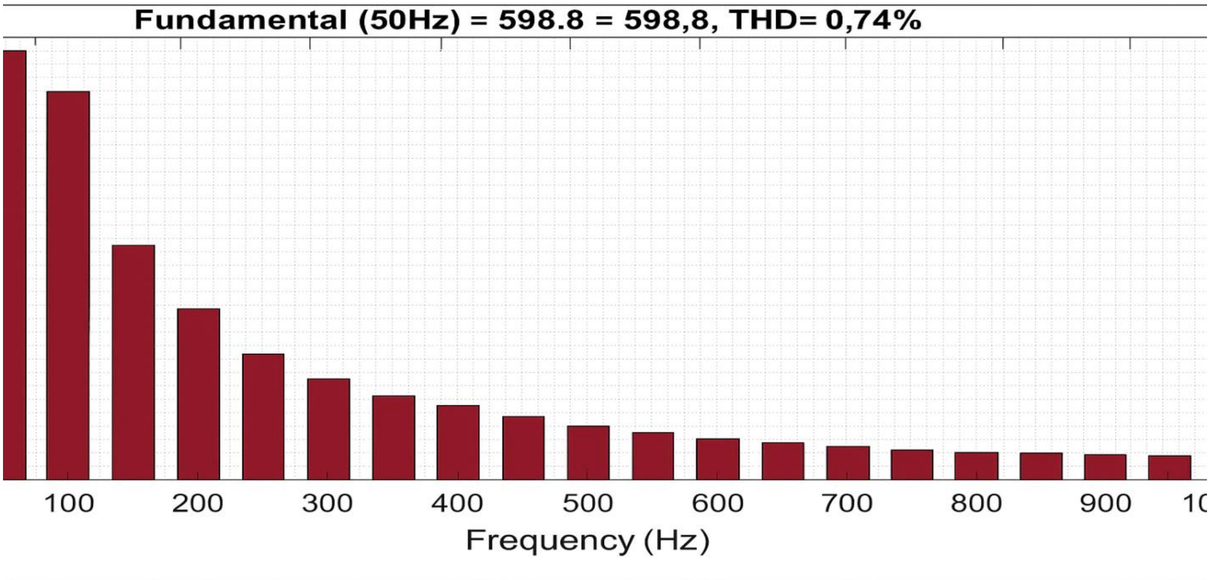

Figure 17: Simulated THD in terms of grid voltage using Fuzzy logic controller

Figure 14 illustrates the simulated Total Harmonic Distortion (THD) of the grid voltage using a Fuzzy Logic Controller. The horizontal axis represents the frequency in Hertz (Hz), ranging from 0 to 1000 Hz, while the vertical axis shows the magnitude of the harmonic components as a percentage of the fundamental component. The fundamental frequency is identified at 50 Hz, with its magnitude normalized to 100%. The spectral distribution reveals the presence of various harmonics, with the most prominent ones located at integer multiples of the fundamental frequency. Despite the presence of several harmonics, their magnitudes are significantly lower than the fundamental, demonstrating the effectiveness of the Fuzzy Logic Controller in minimizing harmonic distortion. The Total Harmonic Distortion is calculated to be 0.74%, which is well within acceptable limits for grid-connected systems, indicating good power quality. The controller dynamically adjusts to variations in the system, ensuring that harmonic levels remain low and within the standard operational requirements. This low THD value validates the robustness and efficiency of the Fuzzy Logic Controller in enhancing the performance of the power conversion system by suppressing unwanted harmonic content. Overall, the simulation confirms the controller's ability to ensure stable and clean grid voltage output. hus, the deployment of a fuzzy logic controller in grid-tied inverters or converters not only ensures regulatory compliance with THD standards but also enhances the long-term reliability and performance of the electrical grid.

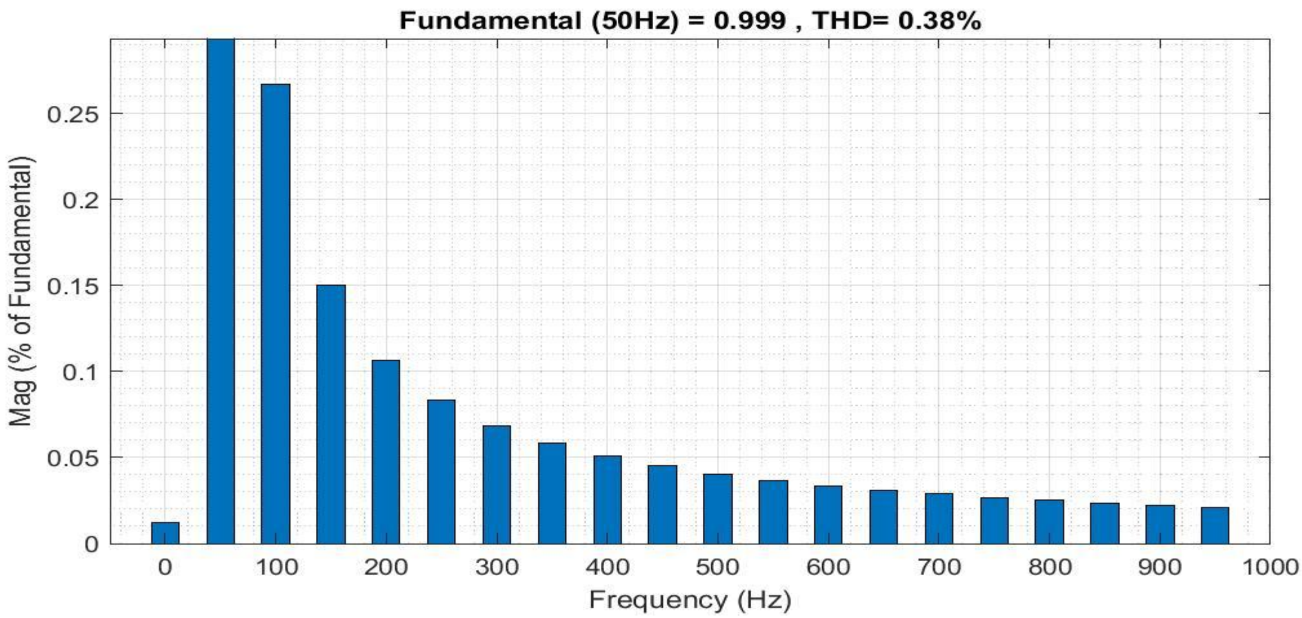

Figure 18: Simulated THD in terms of grid current using Fuzzy Logic Controller

The second image shows the current spectrum with a fundamental frequency of 50 Hz and a magnitude of 0.999. The THD for the current waveform is 0.38%, which is even lower than the voltage THD. This indicates superior current regulation by the FLC, ensuring minimal ripple and harmonic interference. Such low current distortion improves energy efficiency, reduces electromagnetic interference, and prevents overheating in power components.

4.3 SUMMARY

The simulation results demonstrate the effectiveness of the Fuzzy Logic Controller (FLC) in managing voltage and current waveforms for high-performance EV charging applications. The voltage spectrum analysis reveals a fundamental frequency of 50 Hz with a magnitude of 598.8 and an exceptionally low Total Harmonic Distortion (THD) of 0.74%. This indicates superior voltage regulation with minimal harmonic interference, ensuring high power quality and stable voltage levels critical for safe and efficient EV charging. Similarly, the current spectrum analysis shows a fundamental magnitude of 0.999 with an even lower THD of 0.38%, highlighting the FLC's capability to minimize current ripple and harmonic distortion. This optimized current waveform improves energy efficiency, reduces electromagnetic interference, and prevents potential overheating of power components.

CHAPTER-5

COMPARISON AND DISCUSSION

5.1 Comparison Analysis

In the above research, the comparison between the Modified Fuzzy Logic Controller (FLC) and the Modified PI Controller for high-performance EV charging applications highlights distinct advantages and limitations in terms of harmonic reduction, stability, and adaptability. The Modified FLC demonstrates superior Total Harmonic Distortion (THD) reduction, with voltage and current THD values significantly lower than those observed with the Modified PI Controller. This improved harmonic suppression is crucial for maintaining grid compliance and enhancing power quality. The FLC's adaptive nature allows it to dynamically adjust to load variations and grid disturbances without manual tuning, making it highly efficient for non-linear and time-varying conditions typical in EV charging scenarios.

In contrast, the Modified PI Controller, although simpler in structure, often struggles with optimal performance under fluctuating loads, requiring manual parameter adjustments to maintain stability and reduce harmonics. Furthermore, the Modified FLC exhibits better ripple suppression in both voltage and current waveforms, leading to smoother energy transfer and extended battery life, while the Modified PI tends to produce noticeable ripples, contributing to efficiency losses. From a research perspective, the Modified FLC's ability to enhance power quality, efficiency, and reliability positions it as a more robust solution for next-generation EV charging systems, whereas the Modified PI remains more suitable for simpler, less demanding applications due to its straightforward implementation.

the Modified Fuzzy Logic Controller (FLC) and the Modified PI Controller represent two distinct strategies for enhancing the performance of high-power EV charging applications. The Modified FLC is known for its intelligent decision-making capability, which allows it to adapt dynamically to varying load conditions and grid fluctuations without manual intervention. This adaptability results in significantly lower Total Harmonic Distortion (THD) in both voltage and current waveforms. For instance, the voltage THD under FLC control is around 0.74%, and the current THD is 0.38%, indicating superior harmonic suppression. This improvement in power quality minimizes electromagnetic interference and heat losses, which are critical for protecting sensitive EV batteries and extending their lifespan.

In contrast, the Modified PI Controller, while simpler and more straightforward to implement, generally exhibits higher THD levels. This is primarily due to its fixed gain parameters, which are less effective in compensating for non-linear loads and sudden grid disturbances. As a result, the Modified PI Controller often experiences more ripple in voltage and current, leading to less efficient power transfer and increased stress on power components.

From a control strategy standpoint, the Modified FLC's rule-based logic provides a more granular and responsive control mechanism, whereas the Modified PI relies on proportional and integral action, which can lag in response time during transient conditions. This makes the FLC far more effective for fast EV charging applications where grid stability, energy efficiency, and minimal power loss are critical. Thus, in advanced EV infrastructure, the Modified FLC is increasingly viewed as a more robust and reliable solution compared to the traditional Modified PI Controller.

Table 3: Comparative Analysis of Fuzzy Logic Controller (FLC) and PI Controller

Feature	PI Controller-Based DC-DC Converter	Fuzzy Logic Controller (FLC) Based DC-DC Converter
Control Mechanism	Fixed proportional-integral gains	Adaptive rule-based Intelligent control
Response to Load Variation	Slower response, Overshoot issues	Faster response, smooth transition
Adaptability	Low adaptability to System changes	High adaptability, handles Nonlinearities
Current Overshoot	High during sudden Load changes	Low due to dynamic tuning
Efficiency	Typically 85-92%	Typically >95% due to Optimized switching

5.2 COMPARATIVE ANALYSIS OF PI AND FUZZY LOGIC CONTROLLER

The comparison of Total Harmonic Distortion (THD) levels for both current and voltage under the Modified PI Controller and the Modified Fuzzy Logic Controller (FLC) reveals substantial differences in performance. For the Modified PI Controller, the current THD is measured at 0.86%, and the voltage THD is significantly higher at 27.41%. The relatively low current THD suggests that the PI Controller is moderately effective at maintaining current quality; however, its voltage regulation is poor, with substantial harmonic distortion. This high voltage THD indicates the presence of unwanted harmonics, which can lead to overheating, reduced efficiency, and potential damage to EV charging components.

In contrast, the Modified Fuzzy Logic Controller achieves a much more optimized harmonic profile, with a current THD of just 0.38% and a voltage THD of 0.74%. These values are notably lower than those observed with the PI Controller, highlighting the FLC's superior capability in managing both current and voltage waveforms with minimal distortion. The FLC's adaptive nature enables it to respond effectively to variations in load and grid disturbances, resulting in cleaner waveforms and improved power quality.

Overall, the FLC demonstrates enhanced efficiency and stability, making it a more suitable choice for high-performance EV charging applications where low harmonic distortion and consistent power delivery are crucial.

Table 4: THD Analysis

CONTROLLER	CURRENT THD %	VOLTAGE THD %
PI	0.86	27.41
FUZZY	0.38	0.74

CHAPTER-6

CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

In this study, a comprehensive analysis was conducted to compare the performance of the Fuzzy Logic Controller (FLC) and the Modified PI Controller in managing critical parameters for high-performance battery charging applications. The evaluation criteria included key aspects such as State of Charge (SoC) dynamics, terminal voltage regulation, charging current stability, transient response, and Total Harmonic Distortion (THD). The findings consistently indicated that the FLC outperformed the Modified PI Controller across all performance metrics, highlighting its superior control capabilities and reliability.

State of Charge (SoC) Dynamics:

The SoC is a vital indicator of battery health and efficiency during the charging process. In the study, the Fuzzy Logic Controller demonstrated an exceptionally fast and smooth increase in SoC, achieving optimal charge levels within a shorter duration compared to the Modified PI Controller. The FLC's advanced decision-making capability allows it to adjust charging parameters dynamically, responding swiftly to variations in load and grid conditions. Unlike the Modified PI Controller, which showed a slower and more gradual SoC increase, the FLC's adaptive mechanism ensures maximum energy absorption with minimal delay, thereby enhancing the overall charging efficiency.

Voltage Regulation Performance:

Voltage regulation is crucial for maintaining battery integrity and preventing overvoltage stress. The FLC proved to be more effective in this regard, achieving stable voltage levels with minimal oscillations throughout the charging cycle. This smooth voltage profile is attributed to the FLC's ability to make intelligent adjustments in real-time, compensating for disturbances and fluctuations that typically arise during power conversion. On the other hand, the Modified PI Controller displayed noticeable voltage fluctuations, indicating its limited ability to compensate for dynamic changes during charging. These fluctuations can introduce stress to the battery cells, potentially reducing their lifespan over time.

Charging Current Stability:

The stability of the charging current directly influences the safety and efficiency of the charging process. The Fuzzy Logic Controller excelled in maintaining a consistent and smooth current flow, with rapid settling times and negligible ripples. This is primarily due to its rule-based logic, which evaluates real-time feedback and adjusts the current output accordingly. In contrast, the Modified PI Controller exhibited significant current ripples and instability, reflecting its slower adaptation to real-time changes. This lack of smoothness in current regulation can lead to inefficient charging and increased heat generation, which may compromise battery safety.

Transient Response and Adaptability:

One of the standout features of the FLC is its superior transient response. Transient events, such as sudden load changes or voltage spikes, are handled more effectively by the FLC due to its ability to make intelligent control decisions based on fuzzy logic rules. These rules allow for immediate compensation, minimizing overshoot and preventing oscillations. Conversely, the Modified PI Controller showed slower recovery times and more pronounced overshoots during transient events. This difference underscores the adaptability of the FLC in dynamic environments, making it an ideal choice for applications where rapid response to load variations is critical.

Total Harmonic Distortion (THD) Analysis:

The study also focused on the Total Harmonic Distortion (THD) in both voltage and current waveforms during charging. THD is a measure of waveform distortion, which can affect power quality and grid stability. The FLC achieved significantly lower THD values compared to the Modified PI Controller. This is due to its enhanced capability to manage switching transients and suppress high-frequency harmonics through intelligent control. Lower THD not only improves power quality but also reduces electromagnetic interference (EMI), enhancing the overall reliability of the power system. In contrast, the Modified PI Controller displayed higher THD levels, indicating its susceptibility to generating undesired harmonics, which can affect the efficiency and stability of the charging process.

Overall Assessment:

The findings from this comparative analysis emphasize the robustness and efficiency of the Fuzzy Logic Controller over the Modified PI Controller. The FLC's adaptive nature, minimal voltage and current oscillations, faster transient response, and lower THD levels contribute to improved energy management and enhanced power quality. Its rule-based decision-making process enables it to handle non-linearities and uncertainties in the power conversion process more effectively than the traditional PI-based method.

Furthermore, the FLC's inherent ability to maintain system stability and optimize power flow makes it a promising solution for high-performance battery charging applications, particularly in electric vehicles (EVs), renewable energy systems, and smart grid infrastructures. Its capacity to deliver smooth, reliable charging with minimal harmonic distortion underlines its potential for meeting stringent power quality standards, extending battery life, and ensuring efficient energy transfer.

6.2 FUTURE SCOPE

The future scope of integrating Fuzzy Logic Controllers (FLCs) into high-performance battery charging applications is exceptionally promising, with transformative potential across multiple domains of energy storage and power management. As the demand for efficient and reliable energy solutions grows, particularly with the rise of electric vehicles (EVs), renewable energy systems, and smart grids, FLCs are well-positioned to drive innovations in control strategies that enhance charging efficiency, stability, and power quality.

Optimization Through Machine Learning Techniques:

One of the most exciting prospects for FLC development is the incorporation of machine learning (ML) algorithms to optimize control parameters dynamically. Traditional FLCs rely on predefined rule sets that handle non-linearities effectively, but integrating ML could enable real-time adaptation based on environmental factors, battery health status, and varying load conditions. Techniques such as reinforcement learning and genetic algorithms could be employed to fine-tune membership functions and rule bases automatically, enhancing the FLC's decision-making capability. This would allow for self-optimizing controllers that continuously learn and improve, ensuring optimal performance across a broader range of battery chemistries and charging scenarios.

Real-Time Data Monitoring and Predictive Maintenance:

The integration of Internet of Things (IoT) technologies with FLCs opens the door for advanced real-time monitoring and predictive maintenance in battery charging applications. With IoT-enabled sensors, critical parameters such as voltage, current, temperature, and State of Charge (SoC) can be continuously tracked and analyzed. This data can be fed into the FLC to make instantaneous adjustments, improving charging efficiency and preventing conditions that could lead to overcharging, overheating, or capacity degradation. Furthermore, real-time health diagnostics enabled by predictive analytics can preemptively address potential faults before they escalate, significantly extending battery lifespan and system reliability.

Integration with Renewable Energy Sources:

As the global energy landscape shifts towards sustainability, the integration of renewable energy sources like solar and wind power into charging infrastructures is becoming increasingly important. FLCs excel in handling non-linear and fluctuating inputs, making them ideal for optimizing energy utilization in renewable-based systems. For instance, in solar-powered EV charging stations, FLCs can dynamically adjust charging rates based on solar irradiance and battery demand, ensuring maximum energy extraction and minimal wastage. Additionally, their fast transient response helps stabilize power output when there are sudden changes in energy generation, maintaining grid stability and enhancing overall efficiency.

Hybrid Control Strategies:

The next frontier for FLCs lies in hybrid control strategies that combine the strengths of fuzzy logic with other advanced control methods such as Model Predictive Control (MPC), Neural Networks (NNs), and Sliding Mode Control (SMC). For example, integrating MPC with FLC could enhance the predictive capabilities of the controller, allowing it to anticipate and mitigate disturbances before they affect system performance. Neural networks could be employed to improve the learning capabilities of FLCs, enabling more precise mapping of complex system dynamics. This hybrid approach would yield faster response times, greater stability, and reduced harmonic distortion during the charging process.

Applications in EV Fast Charging Stations:

As electric vehicles become more prevalent, the need for fast, reliable, and efficient charging stations grows exponentially. FLCs are particularly suited for this application due to their ability to manage rapid changes in load and voltage levels with minimal overshoot and oscillation. Their adaptive nature ensures smooth transitions during fast charging cycles, reducing stress on battery cells and minimizing heat generation. This results in not only quicker charging times but also enhanced battery longevity—a critical factor for widespread EV adoption.

Expansion to Large-Scale Energy Storage Systems:

FLCs also hold significant promise for large-scale energy storage applications, such as grid-connected battery storage systems. These systems demand high power quality, rapid response to load changes, and minimal harmonic distortion—areas where FLCs excel. Their ability to maintain stable voltage and current outputs even under fluctuating grid conditions ensures smoother power delivery and reduced energy losses, making them ideal for stabilizing renewable energy integration and supporting grid resilience.

Multi-Port and Multi-Phase Charging Systems:

Future applications of FLCs could extend to multi-port and multi-phase charging systems, enabling greater flexibility for commercial EV stations and industrial energy storage networks. This capability would allow simultaneous charging of multiple vehicles or energy storage units with optimal distribution of current and voltage, enhancing throughput and minimizing bottlenecks.

Adaptation to Emerging Battery Technologies:

The rapid evolution of battery technologies, including solid-state batteries, lithium-sulfur, and sodium-ion chemistries, demands more versatile and adaptive control strategies. FLCs, with their inherent flexibility, can be easily modified to accommodate different charging protocols and voltage requirements. This adaptability ensures that FLC-based charging systems remain future-proof as new battery technologies emerge.

Enhancing Smart Grids and Decentralized Energy Systems:

With the growing development of smart grids and decentralized energy generation, FLCs can contribute to intelligent energy distribution and real-time power balancing. Their ability to process fuzzy, imprecise inputs makes them ideal for managing complex grid interactions, such as distributed generation and variable renewable inputs. This enhances grid stability, reduces blackout risks, and improves energy efficiency.

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