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High-Frequency PI-Controlled Bridgeless PFC Converter for Optimized EV Battery Charging

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Abstract

This paper proposes an charging system for Electric Vehicles (EVs) primarily focuses on two key aspects: enhancing efficiency by optimizing power delivery and minimizing energy losses during the charging process. This ensures faster and more effective battery replenishment. This project proposes an optimized battery charging system for EVs, incorporating a PI-controlled high-frequency resonant bridgeless PFC converter. The system efficiently converts a standard 230V AC supply into a regulated 48V DC output, making it suitable for EV battery charging. The bridgeless topology minimizes conduction losses, significantly improving overall system efficiency.

A hysteresis current controller is integrated within the Pulse Width Modulation (PWM) generator, enhancing the system's dynamic response and stability under varying load conditions. Additionally, dual PI controllers work together to precisely regulate both voltage and current, ensuring optimal battery charging while preventing risks such as overcharging and overheating. This system not only improves energy efficiency but also extends battery lifespan by providing a controlled and stable charging environment. The adoption of high-frequency operation reduces component size and weight, making it more suitable for compact EV designs.

By addressing the increasing demand for efficient, reliable, and sustainable EV charging technologies, this project contributes to broader EV adoption and improved energy management in the transportation sector. The proposed system is implemented and analysed using MATLAB 2021a simulation.

1. INTRODUCTION

The rising concerns over pollution from exhaust emissions, increasing fuel consumption, and the depletion of fossil fuels have accelerated the transition towards electric vehicles (EVs). In response, automobile manufacturers are focusing on producing clean, renewable energy-powered electric cars as an alternative to traditional fuel-based vehicles. As the adoption of EVs continues to grow, developing efficient and reliable charging systems becomes crucial.

In India, car owners typically travel around 35 miles per day, a distance that modern electric vehicles can easily cover. However, one of the primary challenges for EV expansion is charging infrastructure development. Effective battery management systems (BMS) play a key role in optimizing battery performance, while fast-charging solutions are essential to reducing charging time and improving the overall usability of electric vehicles

To address the issue of charging efficiency, advanced chargers with grid-compatible architectures need to be developed. This area has gained significant attention, particularly in the integration of renewable energy sources, EV charging, and photovoltaic (PV) systems. Since the voltage levels produced by batteries and solar panels are generally low, efficient power conversion technologies are necessary to boost power output and improve system performance.

2. LITERATURE SURVEY

Heejune Cha et al [2023] have proposed a novel framework using an integrated power-transportation system structure and operation algorithms are developed to analyze the impact of EVs on the distribution system. As an extension of the concept, an optimal driving model is presented, which includes two types of driving: normal driving and long-distance driving. In vehicle planning, Markov chain is used to determine the mileage and status of the electric vehicle.

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Mohammed Hussein Saleh Mohammed haram et al [2023] have developed the architecture using the SLBs are a great environmental and economical option for ESS. SLBs can be utilized for stationary ESS, putting away abundance renewable vitality and giving reinforcement control when required. This test consists of full tests and presents the results of each test. It depicts the redesigned touch and calculates the potential of solar street light for instant life application in this experiment

Rahulkumar .J et al [2023] have proposed a novel framework using the WRIPT power pad for charging EVs during the in-motion moment. A comparison of different WRIPT coil geometries available for static and dynamic WRIPT applications and their performances from previous studies was made, and a comparison of PTEs was made.

Arman Fathollahi et al [2022] have proposed a novel framework using the long-term stochastic scenario-based mathematical model for allocating and sizing DWC infrastructures considering Evs location-routing, power distribution system (PDS) losses, and transportation network traffic. In the long term, all kinds of electric vehicles can benefit from DWC system and promote more energy usage by solving technical problems.

Yuvaraja Shanmugam et al [2022] have developed the architecture using the parameters involved in grid-tied and PV-integrated DWC systems. The charging couplers included in energetic charging framework were arranged and depicted. Those are utilized within the created framework

Nivedita Naik et al [2023] have proposed a novel framework using the topological modification of a Dual Active Bridge (DAB) converter for bidirectional power transfer in a DC microgrid connected fast EV charging station (EVCS). The relationship of ordinary transformers with LC channels is modeled using GAM and AOCLM techniques, and current and voltage control models are determined independently.

Yunhe Yu et al [2024] have implemented the architecture using the hierarchical MIP EV smart charging algorithm designed for LV distribution grid applications. The concept of SC-Alg includes the constraints and schemes of star switching strategy to handle stochasticity. Soon, SC-Alg was validated and fully investigated in RTDT-based PHIL testbed using real LV propagation system model.

Dong Sik Kim et al [2024] have developed the architecture using the EV charging plans based on combined AC slow and DC fast chargers were compared in terms of minimizing the charging fee according to several representative charging rate plans of South Korea.

Yu Yang et al [2024] have proposed a novel framework using the optimal design of a solar and battery assisted electric vehicle (EV) charging station in southern California, with a focus on maximizing long-term profits while addressing operational uncertainties.

Fenil Ramoliya et al [2024] have implemented a novel framework using the energy consumption and distribution framework for EVs in a smart grid environment for efficient EV charging after analysing the affecting parameters such as location, weekday, weekend, and user. Considering EV data, the point-by-point in-depth evaluation of the generated electricity is based on parameters such as CS (station ID), weekdays, holidays, and customers (user ID) in the previous region (region ID). The most important is the grid-based energy distribution to CS by analysing the energy consumption to achieve EV charging.

3. proposed work system for EV charging

With the increase in greenhouse gas emissions from internal combustion engine vehicles and global warming, electric vehicles have recently attracted attention due to their environmental friendliness. In addition to the current EV regulations in each country, EV penetration needs to reach 30%. Since the increase in energy consumption will have a great impact on energy supply, smart energy equipment and stable operation are needed to manage energy consumption and needs. Electric cars are starting to experience a lot of stress and long charging times due to battery capacity. However, many attempts have been made to develop technologies that will solve these problems. 400 km and longer is more popular worldwide. While electric vehicles have made significant progress due to fast charging technology and better battery performance, the impact of electric vehicles on electricity has also become increasingly serious. Increased power transmission loss, increased loads, power distribution problem, premature aging of transformers, overloading of transmission capacity, system restructuring and expansion of infrastructure are just a few of the problems that may occur due to the impact of electric vehicles on the system. There are two main research groups that address electric vehicles in the workplace.

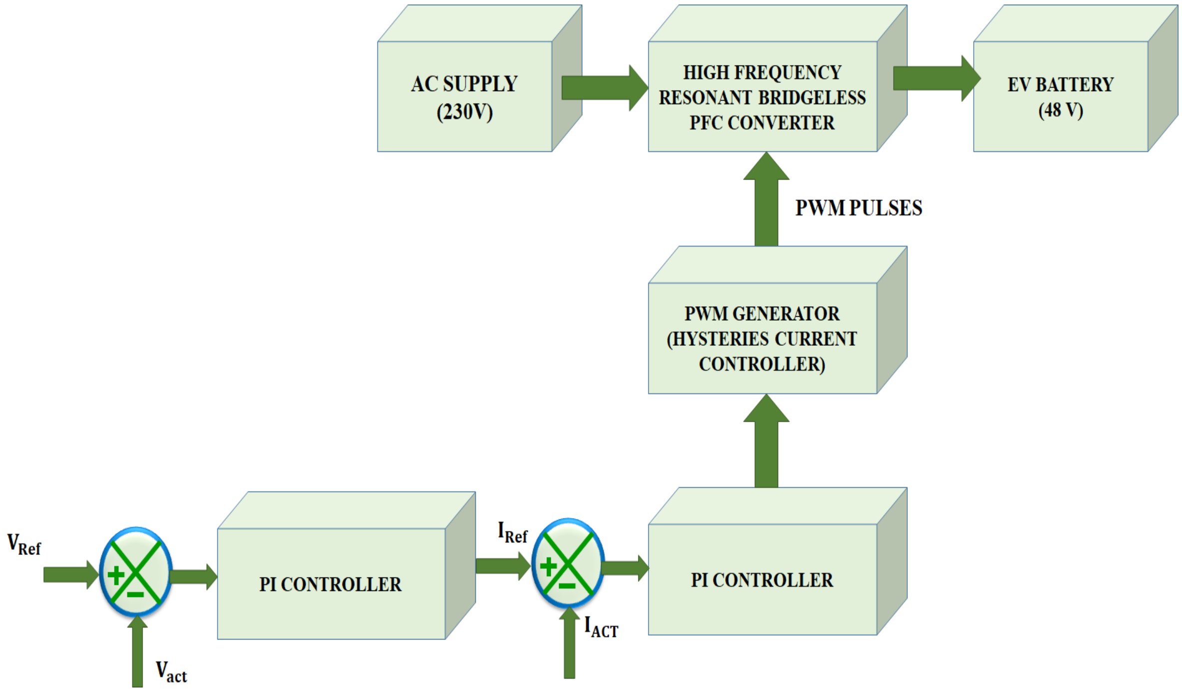

Figure 1 Block Diagram of Proposed Work System for EV charging

3.1 AC supply

To safely use 230V AC power, it is essential to understand key concepts such as voltage, frequency, and safety precautions. Always wear personal protective equipment, including insulated gloves and goggles, and use only insulated tools. Before beginning any installation, disconnect the power at the circuit breaker to prevent electric shock. Gather the necessary tools and equipment, such as electrical meters, connectors, cables, and testing devices like a multimeter. Proper planning is crucial—calculate the total load and select an appropriate circuit breaker to match the power requirements. Creating a wiring diagram helps visualize the connections and ensures accuracy during installation.

Before proceeding, turn off the main power supply and carefully route the wires according to the wiring diagram. Securely connect the live, neutral, and ground wires inside the electrical box, ensuring all connections are tight and properly insulated. Follow manufacturer instructions when installing or replacing electrical outlets. Once the installation is complete, perform a visual inspection to check for loose connections, exposed wires, or faulty insulation. Restore power and test the voltage using a voltmeter, confirming that it reads approximately 230V. Additionally, verify the ground connection to ensure safety and compliance with regulations.

After installation, record the power line details for future reference and troubleshooting. Regular inspections and prompt issue resolution will help maintain safety and ensure the system functions correctly. Adhering to local electrical codes is essential, and consulting a licensed electrician is recommended if there is any uncertainty.

3.2 HIGH-FREQUENCY RESONANT BRIDGELESS PFC CONVERTER

Designing and implementing a high-frequency resonant bridgeless PFC (power factor correction) converter requires a thorough understanding of its working principles, particularly the advantages of a bridgeless configuration in enhancing efficiency by minimizing conduction losses. The process begins with selecting appropriate semiconductor devices, such as MOSFETs or GaN transistors, capable of handling high-frequency switching while maintaining low conduction states. Proper component selection is essential to ensure optimal performance and efficiency.

Once the preliminary design is established, simulation tools like LT SPICE or MATLAB are used to analyse key performance parameters, including efficiency, voltage gain, and compliance with design specifications. These simulations help refine the converter's characteristics before moving to physical implementation. After validating the simulation results, the next

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step involves fabricating the circuit on a printed circuit board (PCB), with careful layout considerations to minimize electromagnetic interference (EMI) and optimize thermal management.

Comprehensive testing is conducted under various load conditions to assess output voltage stability, current-handling capacity, and overall efficiency. A well-implemented control system, typically utilizing a microcontroller or specialized IC, is used to regulate power flow and improve power quality. The final stage involves refining the design based on test results, with a focus on enhancing performance and ensuring compliance with safety standards and electromagnetic compatibility (EMC) regulations. A well-executed design results in a high-frequency resonant bridgeless PFC converter that delivers stable, high-quality power with excellent efficiency.

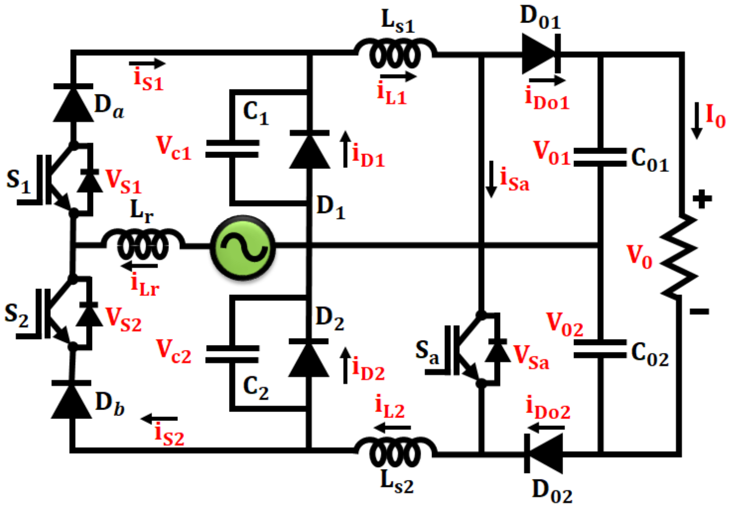

Figure 2 Circuit Diagram of High Frequency BL-PFC Converter

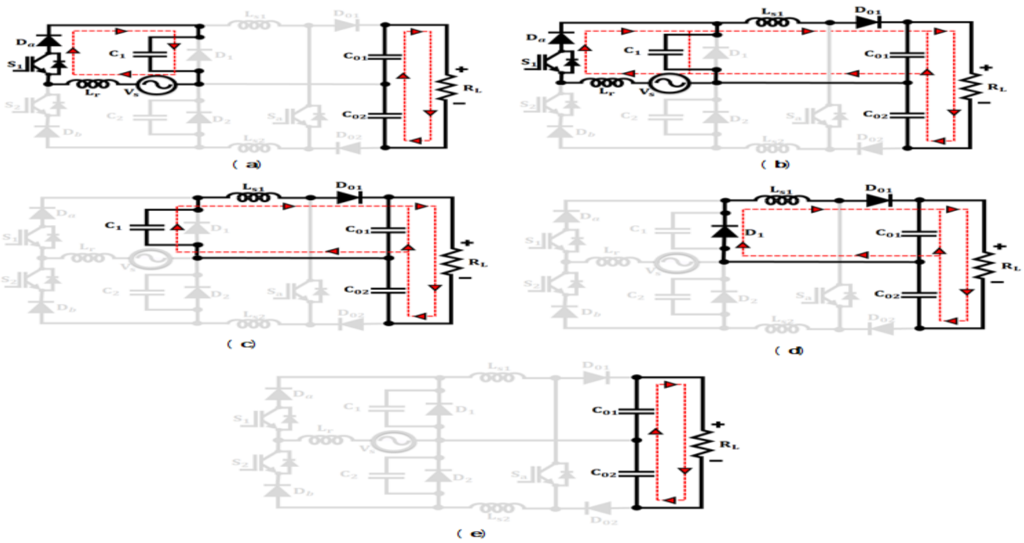

Figure 3 Circuit Diagram of Five Intervals in Operating Mode A

3.3 PI CONTROLLER

Implementing a PI (Proportional-Integral) controller begins with understanding its core components: the proportional term, which reacts to the current error, and the integral term, which accumulates past errors to eliminate steady-state deviations. The process starts by defining the control objectives and identifying the variables that require regulation. Once system requirements are established, a mathematical model is derived using transfer functions or state-space representation to analyse system dynamics.

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Next, selecting appropriate proportional (Kp) and integral (Ki) gains is crucial. This can be achieved through trial-and-error, the Ziegler-Nichols tuning method, or optimization techniques. After determining these values, the PI controller is implemented in either software or hardware, ensuring it can compute the error by comparing the setpoint with the measured process variable. Simulations are then conducted under various conditions to evaluate stability, response time, and overshoot.

Fine-tuning of Kp and Ki is performed as needed to achieve optimal performance. Finally, the PI controller is deployed in the actual system, with continuous monitoring to maintain stability and efficiency. Adjustments are made based on real-world feedback to ensure the system operates as intended, effectively regulating the process while minimizing steady-state errors.

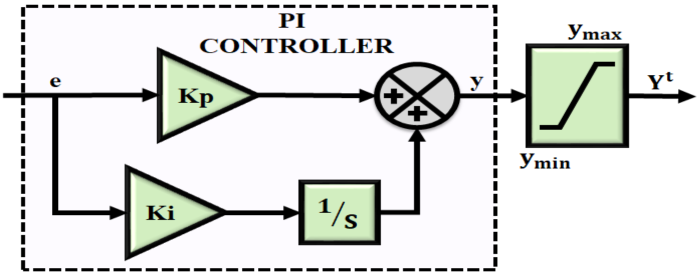

Figure 4 PI Controller

3.3. PWM GENERATOR (HYSTERESIS CURRENT CONTROLLER)

To implement a PWM (Pulse Width Modulation) generator using a hysteretic current controller, it is essential to understand hysteresis control, which regulates current within predefined upper and lower limits. The process begins by defining the required parameters, including the target current and acceptable deviation range. A current sensing circuit is then designed to accurately measure the output current and provide feedback to the controller.

The control algorithm compares the sensed current to the set limits. If the current exceeds the upper threshold, the controller turns off the PWM signal, and if it falls below the lower threshold, the signal is turned back on. This switching process generates a PWM signal to regulate the output effectively. Using a microcontroller or a high-performance PWM IC ensures a sufficiently high switching frequency for smooth control while minimizing noise.

With the PWM generator in place, the system is tested under varying loads to confirm that the current stays within the hysteresis limits. Adjustments are made to the hysteresis band and switching frequency as needed to optimize performance. Continuous monitoring and real-time adjustments ensure stable operation and precise current regulation, enabling effective hysteresis-based PWM control.

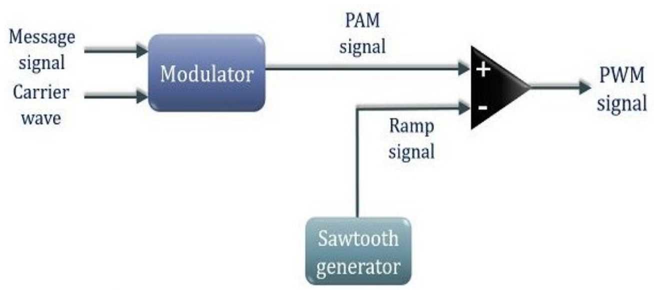

Figure 5 PWM Generator

3.4 EV BATTERY

To install an electric vehicle (EV) battery, begin by defining the power and energy requirements based on the vehicle's performance goals, including range, speed, and weight. Selecting the appropriate battery type, such as lithium-ion or lithium-phosphate, depends on factors like energy density, cost, safety, and lifespan. The battery pack layout is designed by arranging cells in series and parallel to achieve the required capacity while ensuring compliance with electrical standards, reliability, and effective thermal management.

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High-quality batteries should be sourced from trusted suppliers to ensure durability and performance. A battery management system (BMS) is integrated to monitor temperature, individual cell voltage, and the overall state of charge (SOC), enhancing safety and extending battery life. After assembly, comprehensive testing is conducted, including capacity evaluation under different conditions, lifecycle assessment, and thermal performance analysis.

Essential safety measures such as thermal cut-off mechanisms, short-circuit protection, and overvoltage protection are implemented to prevent potential hazards. Once testing is complete, the battery pack is connected to the vehicle's electrical system to verify compatibility with the charging infrastructure. Finally, an optimized charging strategy is developed to enhance charging speed while preserving battery health. This structured approach ensures reliable, efficient, and safe EV battery installations that meet the demands of modern electric vehicles.

4. RESULTS AND DISCUSSIONS

CASE 1 → INPUT VOLTAGE – 230 V

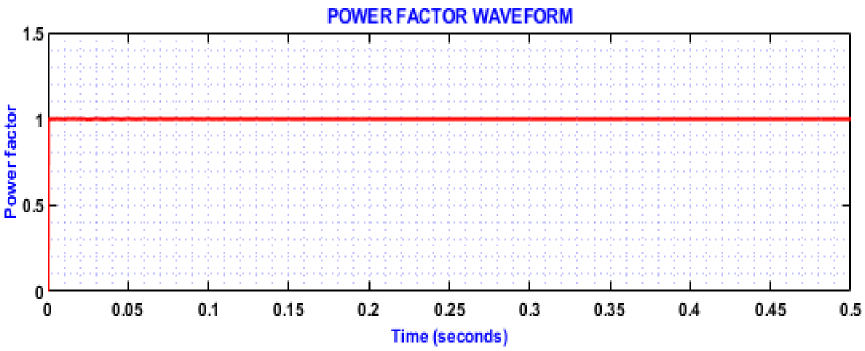

Figure 6 Power Factor Waveform

The fig 6 power factor waveform graph illustrates the relationship between voltage and current in an electrical system over a time span of 0.5 seconds. The horizontal axis represents time in seconds, while the vertical axis shows the power factor, ranging from 0 to 1. The red line consistently hovers near a power factor of 1, indicating optimal efficiency and minimal reactive power.

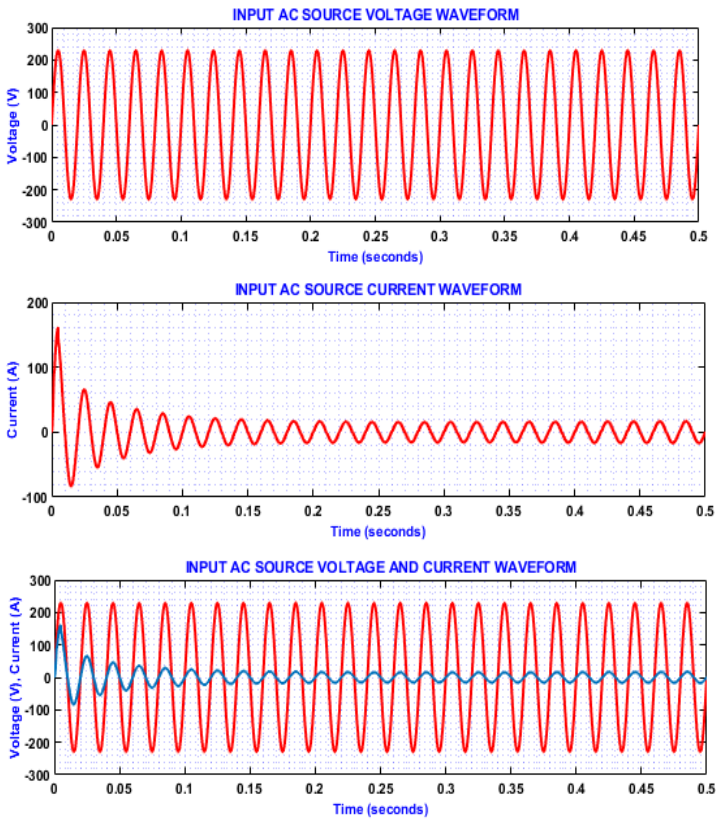

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Figure 7 Input Ac Source Voltage and Current Waveform

The figure 7 input AC voltage and current over a time interval of 0.5 seconds, showcasing their dynamic relationship in an electrical system. The top graph illustrates the input AC voltage waveform, characterized by its sinusoidal shape, indicating the alternating nature of the voltage supply. The mid graph presents the corresponding input AC source current waveform, also sinusoidal, but typically exhibiting a phase shift relative to the voltage, reflecting the system's reactive properties.

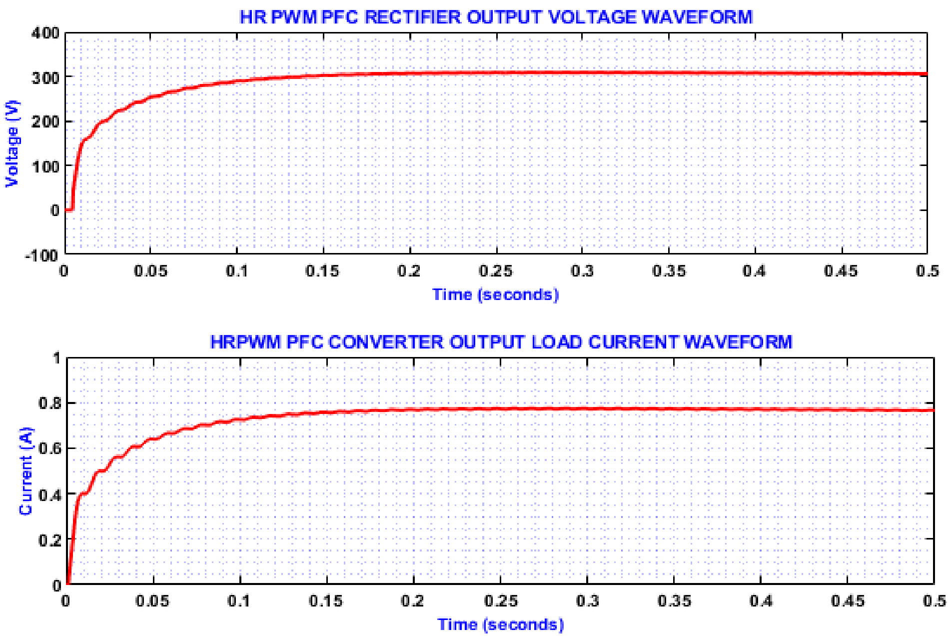

Figure 8 HR PWM Rectifier Output Voltage and Current Waveform

The figure 8 shows a waveforms represent the output of a high-reliability PWM and PFC rectifier and converter over a 0.5-second interval. The top graph shows the rectifier output voltage, which rises quickly and stabilizes around 300 volts, indicating effective voltage regulation.

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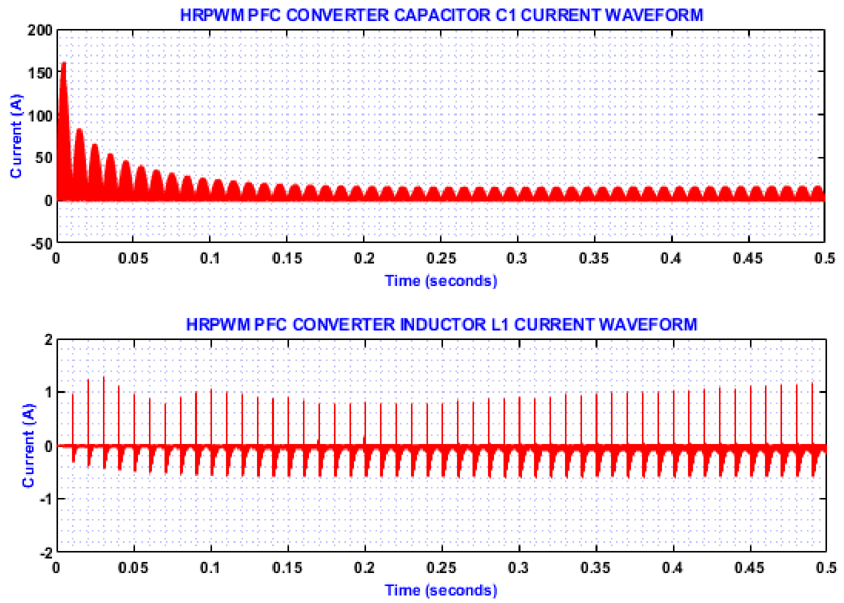

Figure 9 HR PWM PFC Converter Capacitor and Inductor Current Waveform

The figure 9 shows a current behavior in a high-reliability pulse-width modulation (PWM) power factor correction (PFC) converter, focusing on the capacitor C1 and inductor L1 over a 0.5-second interval. The top graph illustrates the capacitor current, exhibiting rapid oscillations before stabilizing, indicative of charging and discharging cycles. The bottom graph shows the inductor current, which fluctuates steadily, reflecting the continuous energy transfer and smoothing effects of the inductor.

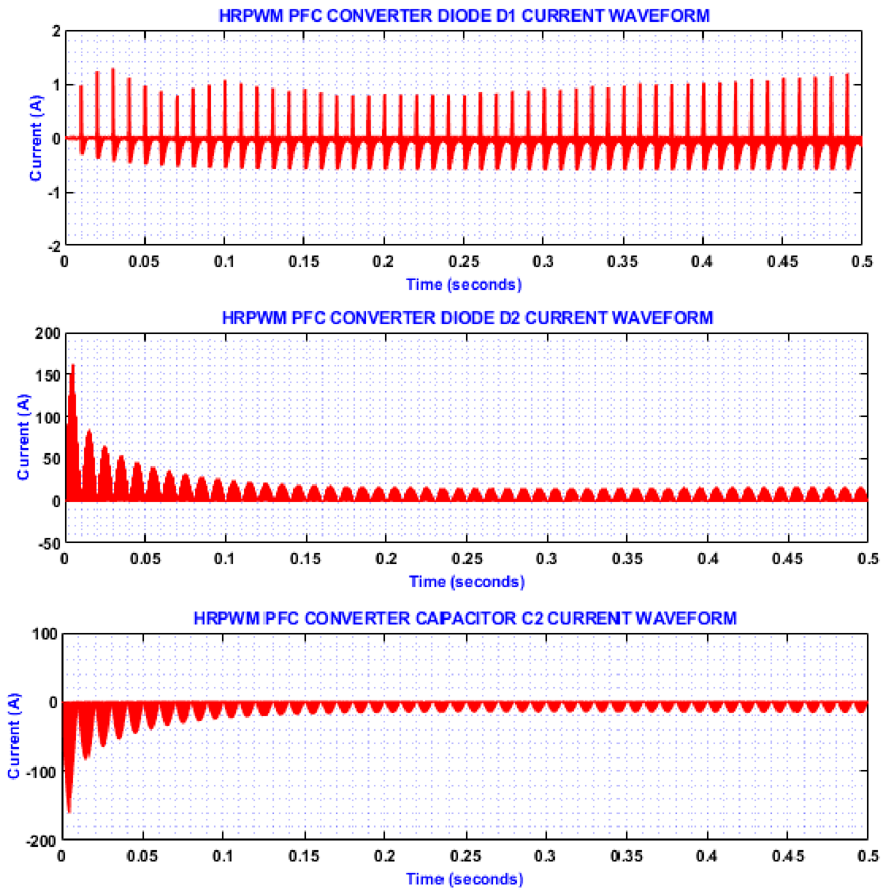

Figure 10 : HR PWM PFC Converter Diode D1, Diode D2 and Capacitor Current Waveform

The figure 10 displays a waveforms illustrate the current characteristics of diodes D1 and D2, as well as capacitor C2, in a high-reliability PWM power factor correction (PFC) converter over a 0.5-second period. The top graph for diode D1 shows a series of rapid current spikes, indicating its switching behaviour during operation. The middle graph for diode D2 similarly exhibits oscillations, reflecting its role in rectification. The bottom graph for capacitor C2 depicts a gradual decline in current, demonstrating its charging and discharging cycles, essential for voltage stabilization in the system.

5. CONCLUSION

The analysis of a simplified 13-level inverter using reduced switched capacitor technology demonstrates significant advancements in multilevel inverter design. This proposed topology effectively overcomes key challenges by reducing component count, streamlining control strategies, and improving overall system efficiency. By utilizing a single DC source and employing the switched capacitor technique, the need for multiple isolated voltage sources is eliminated, resulting in a more compact and cost-effective solution. The self-balancing capability of the capacitors ensures stable and reliable operation without requiring additional circuitry.

Additionally, integrating a PWM generator enhances control precision, leading to efficient harmonic suppression and high-quality sinusoidal output. MATLAB/Simulink simulations confirm the inverter's superior performance, achieving an impressive 98.50% efficiency while maintaining a stepped AC output with minimal total harmonic distortion (THD). These features make the proposed inverter design highly suitable for applications such as renewable energy systems, industrial motor drives, and other high-performance power electronics applications.

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