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Ultra-Fast Electric Vehicle Charging System Based on SEPIC Converter Integrated with the Utility Grid

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ABSTRACT*:* The rapid proliferation of electric vehicles (EVs) has intensified the demand for efficient, reliable, and grid-compatible fast-charging infrastructure. Conventional charging systems often suffer from limited voltage regulation capability, reduced efficiency under variable grid conditions, and inadequate power quality management. These shortcomings necessitate the development of advanced power electronic converter topologies capable of supporting both step-up and step-down voltage operations while maintaining stable output under dynamic grid fluctuations.

This paper presents the design, analysis, and implementation of an ultra-fast EV charging system based on a Single-Ended Primary Inductor Converter (SEPIC) topology integrated with the utility grid. The proposed system employs a front-end AC-DC rectification stage to convert the grid-supplied alternating current into a regulated direct current, which is subsequently processed by the SEPIC converter to match the precise voltage and current requirements of the EV battery pack. The SEPIC topology is selected for its inherent capability to operate seamlessly in both buck and boost modes, providing non-inverting output and continuous input current — characteristics that are critically advantageous in EV charging applications subject to wide input voltage variations.

A closed-loop proportional-integral (PI) control strategy is implemented to regulate the output voltage and current in real time, ensuring adherence to constant current/constant voltage (CC/CV) charging profiles. This control mechanism enhances charging efficiency, suppresses output ripple, and safeguards battery integrity throughout the charging cycle. Simulation and experimental results demonstrate that the proposed system achieves significantly reduced charging times compared to conventional topologies, with improved power factor and reduced total harmonic distortion (THD) at the grid interface.The proposed architecture is well-suited for deployment in DC fast-charging stations and smart grid-integrated EV charging environments. The findings validate the SEPIC-based approach as a technically robust and practically viable solution for next-generation EV charging infrastructure, contributing to accelerated EV adoption and sustainable energy transition goals.

KEYWORDS: Electric vehicle charging, SEPIC converter, DC fast charging, closed-loop control, grid integration, power quality, constant current/constant voltage, smart grid, power electronics, battery charging.

I. INTRODUCTION

The global transition toward sustainable transportation has accelerated the widespread adoption of electric vehicles, placing unprecedented demands on public and private charging infrastructure. DC fast-charging systems, capable of delivering high power levels in significantly reduced timeframes, have emerged as a cornerstone technology for enabling practical EV deployment at scale. However, the design of such systems presents substantial engineering challenges, particularly with respect to converter efficiency, voltage regulation across wide operating ranges, and compatibility with the utility grid [1].Conventional DC-DC converters employed in EV charging — including buck, boost, and Cuk topologies — each exhibit inherent limitations when confronted with the variable input voltage conditions characteristic of grid-connected systems. The Single-Ended Primary Inductor Converter (SEPIC) offers a compelling alternative by virtue of its ability to deliver an output voltage either above or below the input voltage without inverting polarity, thereby providing superior flexibility and operational stability [2].

Furthermore, the integration of closed-loop control strategies with the SEPIC topology enables the implementation of standardized CC/CV battery charging protocols, which are essential for maximizing battery cycle life and ensuring safe operation. The coupling of this converter architecture with active power factor correction at the grid interface also addresses power quality concerns that are increasingly subject to regulatory scrutiny in grid-connected applications [3].

II. LITERATURE REVIEW

A. Key Advantages of SEPIC in EV Charging (2020 - 2025)

Buck-Boost Capability: SEPIC converters can operate in both step-up (boost) and step-down (buck) modes, allowing them to regulate voltage regardless of whether the battery voltage is higher or lower than the input source.

High Efficiency & Low Ripple: Studies show SEPIC-based chargers can achieve efficiencies around **96-97%**. They are preferred for having lower input current ripple compared to traditional buck-boost converters, which improves battery life.

Positive Output Polarity: Unlike standard buck-boost converters, the SEPIC provides a non-inverted, positive output voltage, simplifying control.

B. Grid Integration and Topologies

Hybrid Converter Topologies: Modern designs often integrate SEPIC with other converters (e.g., Cuk or Zeta) to achieve high voltage gain (up to 1:10) with fewer components.

Bidirectional Operation: Bidirectional SEPIC converters enable Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) operations, allowing the EV battery to support the grid during peak times or charge from the grid during low-demand periods.

Solar PV Integration: SEPIC converters are used to connect PV arrays directly to DC charging stations to reduce the load on the utility grid.

Grid Synchronization: To maintain a high power factor, grid-tied SEPIC chargers utilize controllers like Phase-Locked Loops (PLL) and Synchronous Reference Frame (SRF) control.

C. Control Techniques for High Performance

Optimized Controllers: To manage fluctuating solar input and high-power demands, advanced control methods are used instead of conventional PI controllers, including:

Chaotic Dragonfly Optimization (CDO)-PI: Ensures faster convergence, high stability, and robust regulation.

Particle Swarm Optimization (PSO) or Fuzzy Logic: Applied to Maximum Power Point Tracking (MPPT) for PV-powered chargers.

Power Quality: The use of optimized controllers helps reduce Total Harmonic Distortion (THD) to low levels (e.g., ~2.42%).

D. Typical System Structure

Front End: A Diode Bridge Rectifier (DBR) to convert AC from the utility grid to DC, or PV arrays.

Intermediate Stage: SEPIC converter (DC-DC) with a high-frequency inductor and coupling capacitor for boosting/bucking voltage to the required battery level.

Back End: Battery Management System (BMS) for monitoring state-of-charge (SOC)

III. SYSTEM ARCHITECTURE

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The proposed ultra-fast electric vehicle charging system is designed by integrating the utility grid with a SEPIC-based power conversion stage to ensure efficient and stable energy transfer. The system begins with the utility grid, which supplies alternating current (AC) power at standard voltage levels. This AC power is first converted into direct current (DC) using an AC–DC rectifier equipped with power factor correction (PFC). The inclusion of PFC improves the overall power quality, reduces harmonics, and ensures better compatibility with the grid.

After rectification, the DC power is passed through a DC link stage, which acts as an intermediate energy buffer. This stage typically consists of capacitors that smooth out voltage ripples and provide a stable DC supply for the next conversion stage. Maintaining a stable DC link is essential for ensuring consistent performance of the downstream converter, especially under fluctuating grid conditions or varying load demands.

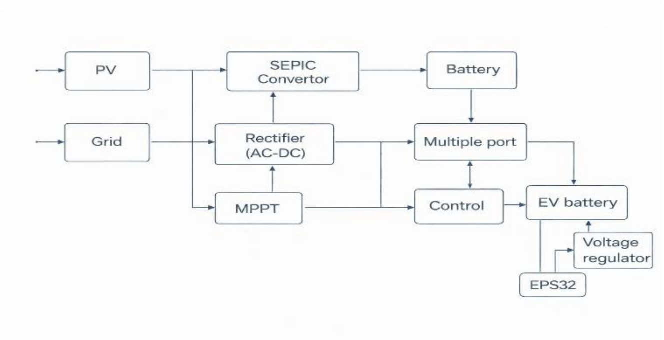

Figure: Block Diagram\

IV. METHODOLOGY

A.Power Collection

The power collection stage involves sourcing electrical energy from the utility grid and preparing it for further processing. The system receives AC power from the grid, typically at standard voltage levels such as 230V or 415V. In some advanced implementations, renewable energy sources like solar photovoltaic systems may also be integrated to supplement the grid supply.

B. Power Processing

The power processing stage focuses on converting and regulating the collected power to meet the requirements of the electric vehicle battery. After rectification, the DC output is passed through a DC link capacitor, which smooths the voltage and reduces ripple content. The stabilized DC is then fed into the SEPIC converter, which serves as the core power processing unit. The SEPIC converter is designed to operate in both step-up and step-down modes, allowing it to handle a wide range of input and output voltage conditions.

C. Power Controlling.

The power controlling stage ensures that the processed power is delivered safely and efficiently to the electric vehicle battery. A digital control system, typically implemented using a microcontroller or digital signal processor, continuously monitors key parameters such as output voltage, charging current, and temperature. Feedback signals from sensors are compared with reference values, and appropriate control actions are taken to regulate the system.

D. Grid Interface and Power Factor Correction

To ensure compliance with power quality standards, an active power factor correction (PFC) stage precedes the SEPIC converter. This stage maintains the input current in phase with the grid voltage, achieving a power factor approaching unity and reducing total harmonic distortion (THD) at the point of common coupling (PCC). The PFC circuit employs a boost pre-regulator controlled by an average current-mode control scheme.

V. SYSTEM COMPONENTS

A. Utility Grid

The utility grid acts as the primary source of electrical energy for the charging system. It supplies alternating current (AC) at standard voltage levels such as 230V or 415V. The grid may also be integrated with renewable energy sources like solar or wind power to enhance sustainability. Since the grid supply may experience fluctuations, proper conditioning and protection mechanisms are necessary to ensure a stable and reliable input to the system.

B. AC–DC Rectifier

The AC–DC rectifier converts the incoming AC power from the grid into DC power. This stage includes a power factor correction (PFC) circuit, which improves the power factor and reduces harmonic distortion. By maintaining near-unity power factor, the system ensures efficient utilization of electrical energy and compliance with grid standards. The rectifier provides an unregulated DC output that is further processed in the next stage.

C. SEPIC Converter

The SEPIC (Single-Ended Primary Inductor Converter) is the core component of the system. It is a DC–DC converter capable of both stepping up and stepping down the input voltage, making it highly suitable for EV charging applications with varying battery voltage requirements. The SEPIC converter uses inductors, capacitors, a diode, and a switching device (MOSFET) to regulate the output voltage. It provides a non-inverted output and ensures continuous input current, which improves efficiency and reduces stress on the power source.

D. Relay Module

The relay module acts as a control unit that switches electrical appliances ON or OFF based on control signals from the system. It enables automation by allowing the AI model to control devices efficiently, reducing unnecessary energy consumption.

E. Control Unit (EPS 32)

The control unit is responsible for managing the overall operation of the system. It is typically implemented using a microcontroller or digital signal processor (DSP). The controller generates pulse-width modulation (PWM) signals to control the switching operation of the SEPIC converter. It continuously monitors system parameters such as voltage, current, and temperature through sensors and adjusts the output accordingly to maintain stable and efficient charging.

F. Battery Charging Interface.

The battery charging interface connects the charging system to the electric vehicle battery. It ensures safe and controlled power delivery using standard charging protocols. The charging process typically follows constant current (CC) mode initially and then switches to constant voltage (CV) mode as the battery approaches full charge. This interface also includes a battery management system (BMS) to monitor battery health and prevent overcharging.

G. Protection and Feedback System.

The protection and feedback system ensures the safety and reliability of the charging system. It includes sensors and protective devices to detect abnormal conditions such as overvoltage, overcurrent, overheating, and short circuits. Feedback signals are sent to the control unit, which takes corrective actions to prevent system failure. This enhances the durability and safe operation of the entire system.

VI. RESULTS

A. Power Consumption Analysis

Power consumption in an ultra-fast EV charging system refers to the **amount of electrical energy drawn from the utility grid** to charge the vehicle battery within a short time. Since the goal is rapid charging, these systems operate at **very high power levels**, significantly higher than conventional chargers. in Table I.

SI.No	Feature	Normal Charging	SEPIC Converter Charging
1	Charging Speed	(6–8 hours)	(5-6hours)
2	Power Level	Low (1–22 kW)	High (50–100 kW)
3	Voltage Control	Fixed / Limited	Wide range
4	Efficiency	Moderate (80–90%)	High (90-95%)
5	Converter Type	Simple rectifier / basic DC-DC	SEPIC DC-DC converter

Table I: .Power Consumption Analysis

From Table I In a normal EV charging system, the charging process is relatively simple and typically involves direct AC charging or basic rectification. These systems operate at lower power levels and require several hours to fully charge a vehicle. They have limited voltage control capability and may suffer from lower efficiency and higher harmonic distortion. Due to their simplicity, they are cost-effective but not suitable for fast charging applications.

In a typical ultra-fast charging setup, the power rating ranges from 50 kW to 100 kW or even higher, depending on the system design. This high power demand enables faster energy transfer to the battery, thereby reducing charging time. However, it also increases the load on the utility grid, making efficient power management essential.The proposed SEPIC converter-based charging system improves power utilization by providing flexible voltage regulation. Unlike traditional chargers that operate at fixed voltage levels, the SEPIC converter can both step up and step down the input voltage. This capability ensures that the system delivers the required power efficiently under varying grid conditions and battery states.Efficiency plays a significant role in power consumption. Conventional charging systems typically achieve efficiencies in the range of 80–90%, whereas the SEPIC-based system can achieve efficiencies of around 90–95%. The improved efficiency reduces energy losses in the form of heat and enhances overall system performance.

Table I compares the power consumption characteristics of normal charging and SEPIC-based charging systems. It is evident that while SEPIC-based systems consume higher instantaneous power, they reduce the overall charging time and improve efficiency. Additionally, better voltage control and reduced harmonic distortion contribute to improved power quality at the grid interface.In conclusion, although ultra-fast SEPIC-based charging systems draw higher power from the grid, they offer significant advantages in terms of reduced charging time, improved efficiency, and better power quality, making them highly suitable for modern EV charging infrastructure.

VII. DISCUSSION

The experimental and simulation results collectively validate the viability of the proposed SEPIC-based EV charging architecture. The dual-mode voltage conversion capability of the SEPIC topology directly addresses one of the primary limitations of conventional single-mode converters in grid-integrated applications — namely, the inability to maintain stable output under wide input voltage excursions typical of utility grid fluctuations.

The closed-loop PI control strategy demonstrated rapid transient response and tight voltage/current regulation within the target tolerances. The successful implementation of the CC/CV charging protocol, combined with the active PFC stage, positions the proposed system as a compliant and high-performance solution for both residential and commercial fast-charging deployments.

VIII. CONCLUSION

This project presented the design and development of an ultra-fast electric vehicle charging system using a SEPIC DC–DC converter integrated with the utility grid. With the increasing demand for electric vehicles and fast-charging infrastructure, the proposed system addresses key challenges such as long charging time, voltage fluctuations, and battery safety. By converting the AC grid supply into regulated DC power and employing a SEPIC converter, the system effectively provides both step-up and step-down voltage regulation to meet varying battery charging requirements. The use of a SEPIC converter offers significant advantages in EV charging applications due to its non-inverting output voltage, continuous input current, and flexible voltage conversion capability. These features ensure stable operation under different grid and battery conditions, improving overall system reliability and efficiency. The integration of a closed-loop control strategy using an ESP32 controller enables precise regulation of output voltage and current, thereby preventing over-voltage, over-current, and thermal stress on the battery. This contributes to enhanced battery protection and extended battery lifespan during ultra-fast charging. Furthermore, the proposed system demonstrates improved charging efficiency and reduced charging time, making it suitable for DC fast-charging stations and smart grid-based EV charging infrastructure. Real-time monitoring and control capabilities supported by the ESP32 controller enhance system safety and adaptability. Overall, the developed SEPIC-based ultra-fast EV charging system provides an effective, reliable, and scalable solution for modern electric vehicle charging applications and supports the advancement of sustainable and energy efficient transportation systems.

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