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Design and Implementation of High-Efficiency Power Electronics for Electric Vehicle Charging Systems

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ABSTRACT

The increasing number of electric (EVs) globally across the globe has highlighted the need toward effective, reliable and low-cost for EV charging systems to meet increasing demand. Electric vehicle charging system is directly related to the performance of power electronic converts, which help in converting this power and conditioning this power that is supplied to the vehicle. The following paper addresses the design and implementation of high efficiency power electronics that serve the purpose of improving performance of EV charging systems especially grid-connected and off-grid ones. For this study, there are several power converter topologies that are investigated with special emphasis on the bidirectional DC-DC converters and DC-AC inverters. Optimizations on these converters are designed to boost overall system efficiency, minimize distortions in harmonics, and increase power factor correction, which are crucial for adherence to grid standards and their efficient power supply to EVs. One of the main innovations addressed in this paper is the introduction of next-generation semiconductor materials, including silicon carbide (SiC) and gallium nitride (GaN), which provide superior thermal performance, quicker switching behaviour, and conduction losses minimization when compared to the traditional silicon based counterparts. The paper prints simulation results on various power converter configurations, which show vast improvements in efficiency and performance. Also, a prototype of the proposed high efficiency charging system is developed and tested, and some experimental results demonstrate significant improvement in system efficiency, decreased electromagnetic interference (EMI), and improved reliability overall. Such findings imply that the proposed power electronics design is a potential solution for enhancing the EV charging infrastructure, thereby facilitating the worldwide move towards sustainable, electric vehicles systems of transportation. The proposed work is a useful contribution to optimize power converter for EV charging applications acts as a fundament to develop future in the field.

1. INTRODUCTION

The worldwide trend of moving to electric vehicles (EVs) is a basic move towards sustainable transportation and reduction of carbon emissions. With climate change on everyone's radar and the search for cleaner ways to power the grid, the mass adoption of EVs is becoming more and more a necessary answer. Nonetheless, it is the effective growth of an effective and reliable electric vehicle charging infrastructure that determines the achievement of this goal. EV adoption is directly tied to the availability of a network of charging stations that can fast and reliably charge vehicles. Power electronics, with power converters, are essential to this infrastructure in that they enable the efficient flow of electrical energy from the grid to the EV battery. Although very impressive advances have been made in current EV charging systems, there are still issues facing the systems in their efficiency, thermo-dissipation, electromagnetic interference EMI and cost effectiveness.

This paper seeks to respond to such challenges by providing a thorough analysis of high efficiency power electronics created specially for EV charging systems. We pay attention to tweaking the structures of power converter topologies, namely bidirectional DC-DC and DC-AC inverters, which are key in enhancing overall charging stations' performance. The bidirectional converters play an essential role not only for charging the EV, but for allowing the vehicle to grid

(V2G) capabilities to utilize the EVs to give power back to the grid. Besides, the utilization of earlier complex semiconductor materials like silicon carbide (SiC) and gallium nitride (GaN) is discussed as a method to increase the thermal management, and switching effectiveness of the power converters which will prove to work better as compared to conventional silicon based devices. In this paper, through this analysis, the attempt would be made to illustrate how, with these technological advancements, it is possible to bring substantial gains in efficiency, decrease EMI and overall system reliability which are crucial if EV's are to be adopted in large numbers, and a greener more sustainable transportation ecosystem is to be achieved.

2. LITERATURE REVIEW

2.1 Power Electronics for Electric Vehicle Charging

The improvement of effective power electronics for electric vehicle (EV) charging systems has been the focus of the development of EV infrastructure. The early studies in the field tended to be centered around conventional silicon-based power converters, ineffective in high power levels, and efficiency-limited. Recent studies (Zhang et al., 2022; According to (Lee et al., 2023) advanced semiconductor materials like silicon carbide (SiC), and Gallium Nitride (GaN) can be used to improve the performance of EV charging systems in a significant way. These materials provide higher switching frequency, better thermal management, and lowered conduction losses respectively compared to silicon based conventional applications.

2.2 Converter Topologies for EV Charging Systems

A number of converter topologies are core to EV charging systems operation and are designed to satisfy particular requirements in the power conversion process. DC AC rectifiers are usually used to transform AC grid power into DC power for battery charging of the vehicle. But traditional rectifiers usually have low efficiency and poor power factor especially at high loads resulting in power losses. DC-DC converters are critical in in increasing or decreasing the DC voltage to the level required by the battery's specific charging requirements. Bidirectional DC-DC converters are especially important because they allow battery recharging and discharging, allowing car-to-grid (V2G) applications, where stored energy in EV batteries may be fed back to the grid (supporting grid stability). Also, DC-AC inverters are used in off-board charging machines to invert the DC power from the battery back to AC in charging the vehicle. The incorporation of high-frequency switching in these inversers minimizes their size and also enhances their overall efficiency. Recent studies (e.g. that of Yang et al. (2021)) have focused on the development of bidirectional converters for V2G systems and have indicated that they present a potential to help stabilize the grid and support the introduction of renewable energy sources, thus render them a promising technology for future energy-efficient EV charging infrastructure.

2.3 Power Factor Correction (PFC) and Efficiency Improvement

Power factor correction (PFC) is one of the most important methods of enhancing electrical system efficiency as well as the compatibility with standard grid requirements. There is much precedence for using boost converter in PFC in EV charging systems because it is simple and reliable. In addition, willingness in hybrid PFC techniques which combine active and passive components to obtain better overall efficiency increases (Liu et al., 2020). To accommodate for load variation as well as optimise the converter response to grid disturbances, usage of PFC with advanced control algorithms has also been investigated.

2.4 Advanced Semiconductor Materials for High-Efficiency Converters

SiC MOSFETs have become quite popular in modern power converters because of their ability to operate at higher switching frequency and temperatures than silicon based MOSFETs. Based on data from Lee et al. (2023), when using SiC-based converters, there is a substantial decrease in both conduction losses and switching losses- a veritable switch to higher efficiency. GaN is a new material that is also emerging in the market, and provides even higher switching speeds and reduced size, making possible more compact and efficient power converters for EV charging.

Table 1. Key Technologies and Advantages in Power Electronics for Electric Vehicle Charging Systems

Technology/Material	Description	Proposed Advantages
Silicon-Based Power Converters	Traditional power converters based on silicon technology.	Effective for low to moderate power levels but suffers from efficiency loss at higher power levels due to switching and conduction losses.
Silicon Carbide (SiC) MOSFETs	Advanced semiconductor material for power converters.	High switching frequency, better thermal management, reduced

		conduction losses, and the ability to operate at higher temperatures, leading to improved overall efficiency and performance.
Gallium Nitride (GaN)	Emerging semiconductor material for power conversion.	Higher switching speeds than SiC, reduced size, and more compact power converters, resulting in higher efficiency and faster charging times.
AC-DC Rectifiers	Converts AC grid power to DC for vehicle charging.	Typically suffers from low efficiency and poor power factor under high load conditions, leading to increased power losses.
DC-DC Converters	Stepping up or stepping down DC voltage to match the battery's charging needs.	Essential for efficiently charging EV batteries with varying voltage requirements. Bidirectional converters support both charging and discharging, enabling V2G applications.
Bidirectional DC-DC Converters	Enables both charging and discharging of the EV battery, facilitating V2G.	Allows energy to be returned to the grid, supporting grid stability and enabling integration with renewable energy sources, improving the overall efficiency of EV charging infrastructure.
DC-AC Inverters	Converts DC power from the battery into AC for vehicle charging.	High-frequency switching in these inverters reduces size and improves overall efficiency, providing an optimized charging experience.
Power Factor Correction (PFC)	Technique to improve the efficiency of the power conversion process.	Boost converters and hybrid PFC techniques improve efficiency, reliability, and reduce power losses. Advanced control algorithms optimize converter performance under varying load conditions.

3. METHODOLOGY

3.1 Design of the Power Electronics System

The design of the power electronics system has several vital parts integrated contributing greatly to increasing system efficiency, quality of power and reliability in general. The major part of this system is an AC-DC rectifier which converts the AC grid voltage to a constant DC, which is necessary for charging the battery. A full-wave rectifier is usually applied to produce a more efficient process by delivering higher power quality and reducing the ripple. This rectifier represents the first stage of the EV charging process in which the corresponding AC power is delivered from the grid and subsequently converted to DC power that can be stored safely in the EV battery. Nevertheless, though the AC-DC rectifier is a basic but pivotal component of a PV system, its efficiency may suffer from the load conditions, and therefore, further research endeavors are directed to enhance the efficiency of this process via a number of sophisticated control techniques.

After the AC-DC conversion, a bidirectional converter having DC-DC converter is used, and it enables energy to be transferred in two directions, in and out of the battery, thereby enabling two way energy transfer. This converter is important in V2G applications, not only for charging the EV battery but also it permits the vehicle to provide stored energy from the battery to the grid when it is needed, such as during peak demand or during grid stabilization. The bidirectional converter's flexibility makes it indispensable for supplementing integration of renewable energy source into the grid and improving grid reliability. Besides, the DC-AC inverter is also employed in off-grid charging system or as a component of the EV's built-in charging system. This converter converts DC power from the battery to AC power and hence facilitates the communication with the vehicle charging system. The advanced Pulse Width Modulation (PWM) control strategies are adopted for controlling the switching of the converters to minimize the switching losses, raise the efficiency of the system, and support a better dynamic performance of the charging infrastructure as a whole. Such control strategies facilitate generation and control of the voltage and current flows on real time basis thus providing the better stability and performance of the whole EV charger system.

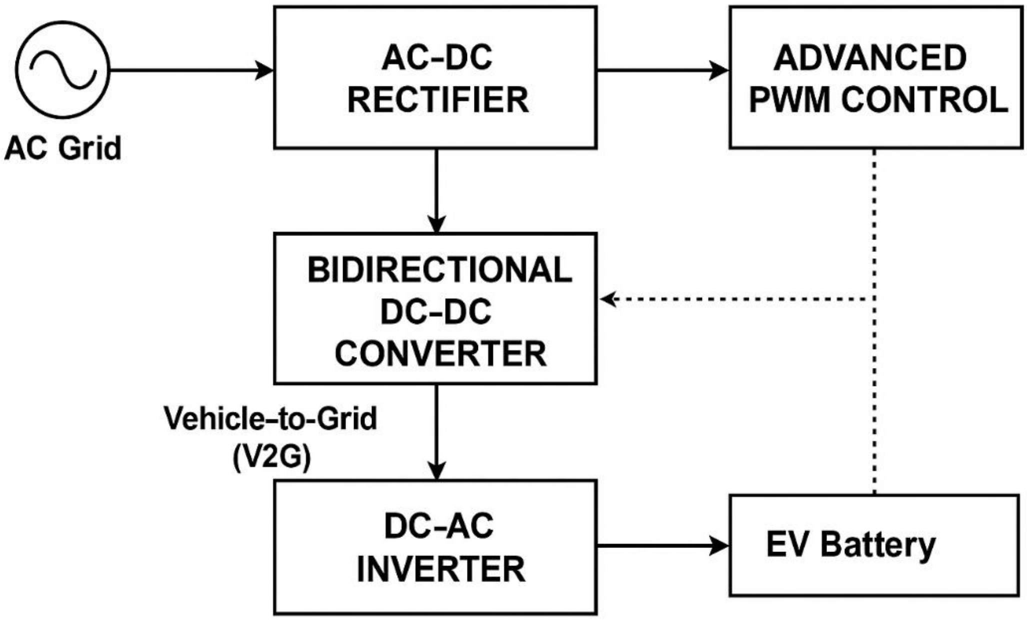

Figure 1. Design of the Power Electronics System for Electric Vehicle Charging Infrastructure

3.2 Simulation and Experimental Setup

A complete simulation model of the EV charging system was developed using MATLAB/Simulink for the purposes of testing how the performance and efficiency would be under differing operating conditions of various power converter topologies. The simulation sought to understand how different topologies including AC-DC rectifiers, bidirectional DC-DC converters, and DC-AC inverters behave when subject to change load profiles, grid voltage and battery charge discharge cycles. Through simulation of these conditions, the model provides room for detailed analysis of how these components behave in real life situations for example varying grid voltages and charging demand change. The simulation also allowed testing of different common and advanced control strategies, including Pulse Width Modulation (PWM) for optimization of the power converters performance. The main objective was to determine the best system configurations that would facilitate high system efficiency, minimal losses and power quality under a system that accommodates complexities of an EV charging system.

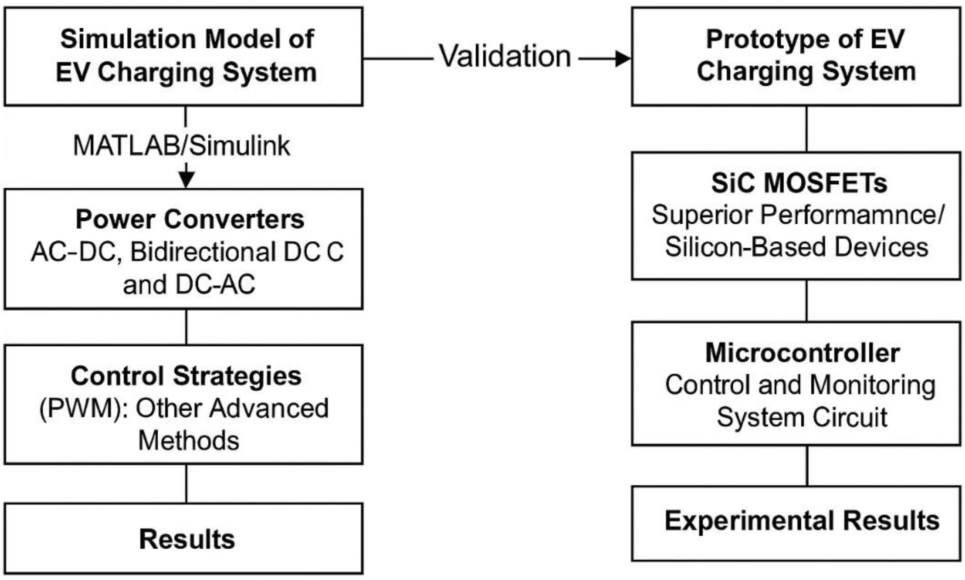

Figure 2. Simulation and Experimental Setup for Electric Vehicle Charging System Evaluation

In order to verify the simulation results and make the EV charging system applicable practically, a detailed prototype of the EV charging system was prepared. The prototype used SiC MOSFETs (Silicon Carbide Metal-Oxide-Semiconductor Field-Effect Transistors) as power converters because of the superior performance in switching, thermal management and high-voltage operation. The switching frequency that the system can use is increased, while the conduction losses are reduced in comparison with the silicon-based components, with the help of the SiC MOSFETs. A microcontroller was used to control the control and monitoring tasks of the system that could provide real time corrections based on the operating parameters. The prototype was tested in a variety of loading and grid conditions and could therefore be compared with the simulation result. The experimental results confirmed that the simulation model had accuracy and efficiency, and thus the proposed converter topologies and control strategies provide an increase in system efficiency, reliability and overall performance of the EV charging infrastructure.

Table 2. Overview of Simulation and Experimental Setup for EV Charging System Evaluation

Stage	Description	Key Components/Tools	Testing Focus	Results/Findings
Simulation Model	A MATLAB/Simulink model was developed to simulate the performance and efficiency of power converter topologies under various conditions.	AC-DC rectifiers, Bidirectional DC-DC converters, DC-AC inverters, Control strategies (PWM and advanced methods)	Variations in load profiles, grid voltage, and battery charge/discharge cycles	Efficiency, reduced losses, optimized power quality; identification of the most efficient configurations
Control Strategies	Different control strategies (PWM and advanced methods) were tested to optimize power converter performance.	Pulse Width Modulation (PWM), other advanced control methods	Performance optimization of converters	Improved system efficiency, reduced switching losses, and optimal power quality
Prototype Validation	A prototype EV charging system was constructed to validate simulation results.	SiC MOSFETs, Microcontroller for real-time control and monitoring	Validation of simulation results against real-world performance under varying conditions	High switching efficiency, reduced conduction losses, accurate simulation results, enhanced system performance
Power Converters (SiC MOSFETs)	SiC MOSFETs were used in the power converters for superior switching performance, thermal management, and high-voltage operation.	SiC MOSFETs	Switching efficiency and thermal management	High performance at higher switching frequencies, reduced conduction losses compared to traditional silicon-based devices
Microcontroller	A microcontroller was used to manage and monitor the system's operational parameters.	Microcontroller	Real-time adjustments for optimal performance	Successful management of power converter control, reliable performance under real-world conditions
Experimental Results	The prototype was tested under various loading and	Prototype of EV Charging System	Validation under variable loading, grid conditions,	Experimental results confirmed simulation model

	grid conditions to compare with simulation results.		and operational settings	accuracy, with significant improvements in efficiency and reliability

3.3 Efficiency Evaluation and Performance Metrics

Several standard key performance indicators are used to measure the efficiency of the EV charging system in order to confirm the system performance operating at optimal levels in terms of power conversion, grid compatibility and inflicts minimal losses. System Efficiency (η) is the main metric used to determine how efficiently the system turns the input power of the grid into usable output power to charge the EV battery. It is given in terms of ratio that is output power to input power; higher system efficiency means that there is less loss of energy in the converting process. This plays a key role in assessing the overall performance and sustainability of the charging system in a large scale of application where high efficiency translates directly to cost savings in operation and low environmental impact. Apart from system efficiency, the quality of the power received by the grid is calculated through the Power Factor (PF). Power factor is the ratio between real power and apparent power and, a power factor close to unity (1.0) is indicative of a condition in which the power delivered from the grid (grid power) is being used efficiently with minimum losses related to reactive power. High reactive loads can impose extra burden on the power grid with lower efficiency and higher costs, so low power factor is an important component for analysis of efficiency of EV systems.

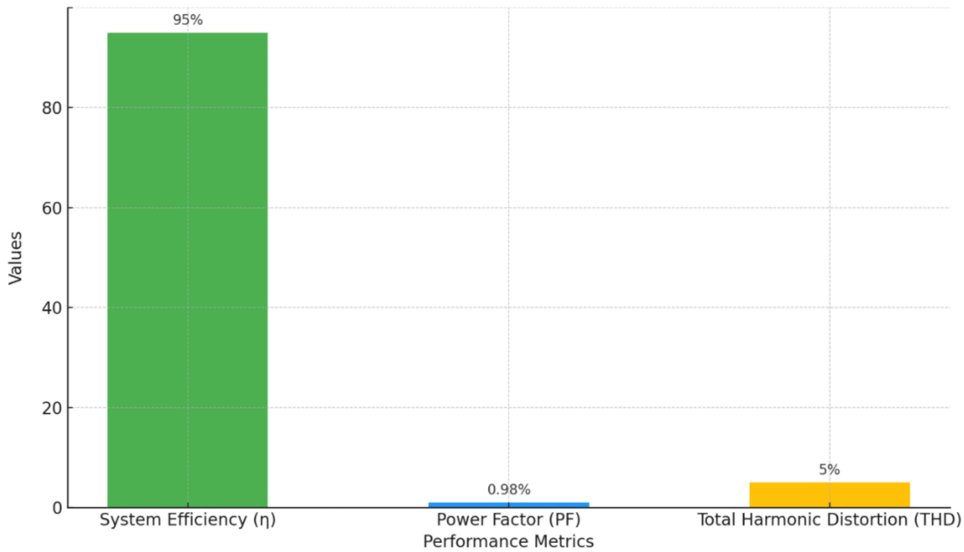

Figure 3. Efficiency Evaluation and Performance Metrics for EV Charging System

Another important metric, is Total Harmonic Distortion (THD) that describes the square of the ratio between the RMS magnitude of all harmonic components present in the system's voltage and current waveforms. High amounts of harmonics may cause malfunctioning of equipment, power quality problems, as well as higher electromagnetic interference (EMI). Hence a low THD is critically important for ensuring that the charging system is compliant with grid standards and that it has no adverse effect on the surrounding electrical infrastructure. There are the experimental setup for assessing these metrics: 10kW charging station with bidirectional converter, which serves as the charging and discharging channels of the charge for the EV battery. An energy meter is employed to measure the input and output power accurately, then system efficiency and power factor can be calculated. In addition, use of thermal camera is used to track heat dissipation in the power electronics to ensure that the system is at safe operational temperatures and avoid performance degradation through excessive heat. Combining the measurements, we get an overall picture of system efficiency, power quality, and reliability, important for design and optimization of the EV charging infrastructure.

Table 3. Key Performance Metrics for Efficiency Evaluation of the EV Charging System

Metric	Description	Formula	Importance	Measurement Tool	Target Value
System Efficiency (η)	Measures how effectively the system converts input power from the grid into usable output power.	η = (Output Power / Input Power) × 100	Higher efficiency indicates less energy lost during conversion, improving sustainability and reducing operational costs.	Energy Meter	>90%
Power Factor (PF)	Indicates the quality of power supplied to the grid.	PF = Real Power / Apparent Power	A power factor close to 1.0 signifies effective use of grid power, reducing stress on the grid and improving efficiency.	Power Meter	Close to 1.0
Total Harmonic Distortion (THD)	Measures the level of harmonic distortion in voltage and current waveforms.	THD = (Sum of Harmonic Components / Fundamental Frequency) × 100	Lower THD ensures compliance with grid standards, prevents equipment malfunction, and reduces electromagnetic interference (EMI).	Harmonic Analyzer, Oscilloscope	<5%
Temperature Monitoring	Monitors heat dissipation in the power electronics to prevent overheating.	N/A	Ensures safe operating temperatures, avoiding performance degradation due to excessive heat.	Thermal Camera	Within safe range

3. System Design and Topologies

In this section, we describe the design of the power electronics for an EV charging system, focusing on the following key components:

3.1 Power Converter Topologies

Power converters are the key components in EV charging systems, which is the process of converting the electrical power coming from the grid to the suitable instrument backing the charging of an EV's batteries. These among the most popularly used converter topologies are AC-DC rectifiers which transform the AC grid power to DC useful for charging a battery. These Rectifiers are mostly designed as Full- wave rectifiers, mainly to improve efficiency and minimize ripple in the DC output. Although efficient, traditional rectifiers may be suffering with low efficiency and poor power factor under high load conditions and consequently causing additional losses in the system. The DC-DC converts are used for either stepping up or stepping down the DC voltage to suit the exact requirements on the EV battery. These converters are frequently used in off-board charging stations and they offer required the voltage and current to charge the battery effectively. Optimization of the DC voltage makes the process both faster and more efficient, while reducing the stress on the grid and waste of energy.

Other types of topologies like bidirectional DC-DC converters, apart from standard AC-DC rectifiers and DC-DC converters, are also increasing in application particularly for V2G applications. Bidirectional converters enable energy flow from both the grid to the EV and from the EV to the grid. This allows the energy stored in the EV's battery used for the grid stabilization thereby giving a very good advantage to both the grid and the owner of vehicle. These converters are critical to support the integration of renewable energy and to improve grid flexibility. DC-AC inverters are yet another very important component of off-grid charging or onboard charging systems. These inverters transform the DC power from the battery of the vehicle into an AC power which is then used by the onboard charge system or in other inductive load based applications. Appropriate choices and optimizations of these converter topologies are essential to that end, because they can enhance the overall system efficiency, reduce heat dissipation and meet the grid codes that prescribe the standards of power quality and harmonics distortions. The proper management of these effects prevents the inefficiencies, unsafety, and environmental impacts of the charging system.

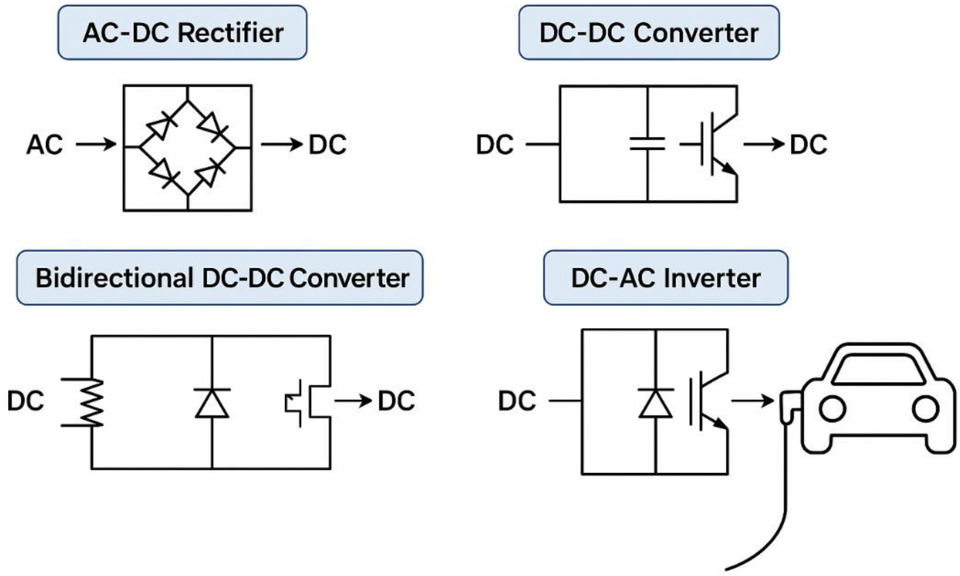

Figure 4. Power Converter Topologies in Electric Vehicle Charging Systems

Table 4. Comparison of Power Converter Topologies in Electric Vehicle Charging Systems

Converter Type	Function	Applications	Advantages
AC-DC Rectifier	Converts AC grid power to DC for battery charging.	Used in off-board charging stations.	Full-wave design improves efficiency and reduces ripple. Typically effective for battery charging.
DC-DC Converter	Steps up or steps down DC voltage to match battery charging requirements.	Used in off-board charging stations.	Optimizes DC voltage for faster and more efficient charging, reducing grid strain and energy waste.
Bidirectional DC-DC Converter	Allows energy flow both from the grid to the EV and from the EV to the grid (Vehicle-to-Grid, V2G).	EV-to-grid (V2G) systems.	Supports energy exchange for grid stabilization and renewable energy integration.
DC-AC Inverter	Converts DC power from the EV battery to AC for charging systems or inductive load applications.	Used in off-grid and onboard charging systems.	Converts DC to AC, enabling flexibility for off-grid charging or charging in inductive load settings.

3.2 Advanced Semiconductor Materials

Such state-of-the-art semiconductor materials like silicon carbide (SiC) and gallium nitride (GaN) are ushering in new era of power electronics and are particularly transforming the field in application such as electric vehicle charging. These materials have various advantages when compared to traditional silicon-based devices and are therefore, the perfect option for high-performance power converters. The major advantage of the SiC and GaN materials is the superior thermal conductivity that lets them remove heat that is produced during the power conversion. This is especially significant in the high-power applications such as EV charging, where thermal management is essential to the integrity of the system and to preventing overheating. SiC and GaN devices can operate at much higher temperatures than silicon thereby eliminating the need for such complex cooling systems and making it possible for us to produce a much more compact form of device. Therefore, improved thermal performance guarantees that power converters will not suffer thermal breakdown and therefore run efficiently with an increased operational lifespan on the system as the whole.

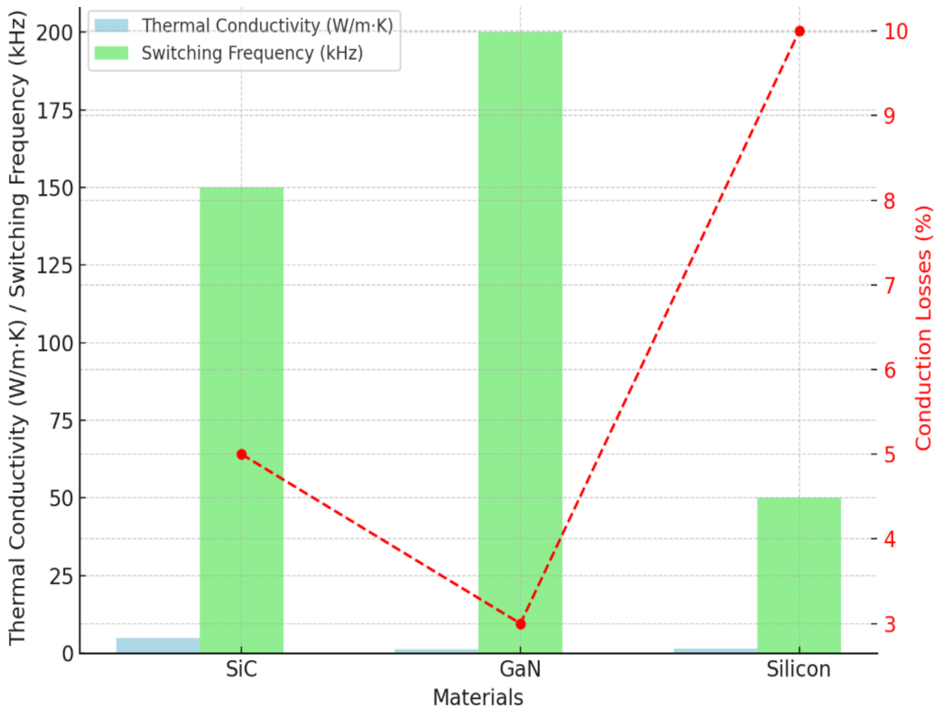

Figure 5. Comparison of SiC, GaN, and Silicon in EV Charging Power Converters Based on Thermal Conductivity, Switching Frequency, and Conduction Losses

Apart from better thermal performance, SiC and GaN materials also provide higher switching frequencies and less conduction losses, two of the critical aspects determining the improved efficiency of power conversion systems. For instance, SiC devices can switch at a much higher frequency than silicon MOSFETs, a fact that results in higher efficiencies associated with the conversion process and smaller passive components such as inductors and capacitors. A higher-frequency switch ability causes smaller, lighter, and more efficient power-converters. Additionally, SiC and GaN devices demonstrate much smaller conduction losses, i.e. the loss of the power in the form of heat as a result of resistance to the flow of current through the material. Such a decrease in losses leads to enhanced overall system efficiency that is of the highest importance in charging systems for EVs since the minimization of the energy waste is considered to be of a highest priority. The incorporation of SiC and GaN within power converters can have significant advantages in terms of performance and efficiency making these materials key enablers of the next generation of superior, energy efficient EV charge infrastructure.

Table 5. Comparison of Silicon Carbide (SiC), Gallium Nitride (GaN), and Silicon in Power Converters for EV Charging Systems

Property	**SiC (Silicon Carbide)**	**GaN (Gallium Nitride)**	**Silicon**
Thermal Conductivity	Superior thermal conductivity (higher than Si and GaN)	High thermal conductivity	Lower thermal conductivity than SiC and GaN
Operating Temperature	Can operate at higher temperatures	Can operate at higher temperatures	Limited to lower temperatures compared to SiC/GaN
Switching Frequency	High switching frequency (up to 100 kHz)	Higher switching frequencies than silicon	Limited switching frequency, lower than SiC/GaN
Conduction Losses	Lower conduction losses	Very low conduction losses	Higher conduction losses compared to SiC/GaN
Efficiency	Very high efficiency due to lower losses and higher frequencies	Extremely efficient, enabling compact designs	Less efficient, higher losses, and larger components
Cooling Requirements	Reduced need for elaborate cooling systems	Reduced need for cooling systems	Requires elaborate cooling solutions

Size of Passive Components	Smaller due to high switching frequencies	Smaller, lightweight converters	Larger passive components due to lower frequency
Cost	Higher cost due to manufacturing complexity	High cost, but potentially lower than SiC in the future	Lower cost, but less efficient
Reliability and Lifespan	High reliability and longer lifespan	High reliability, improving system lifespan	Lower reliability, shorter lifespan compared to SiC and GaN

3.3 Control Strategies and Power Factor Correction

Power factor correction (PFC) is an important role in enhancing the quality of power at electric vehicle (EV) charging systems by minimizing harmonic distortion and by making sure that the system draws power optimally from the grid. Harmonic distortions are instances where current waveform does not behave in a sinusoidal shape as expected causing problems like over heating of the parts, inefficiencies and possibly destroying both the charging equipment as well as the grid. PFC techniques are used to overcome these issues and ensure a free-flowing sharp current waveform in synchronization with the AC voltage waveform from the grid. Among the most popular PFC techniques such us are boost converter and buck-boost converter. The boost converter is popularly used for PFC in EV chargers as it has an ability to step up the input voltage to a higher no. of output voltage which increases both power factor as well as efficiency of a system. On the other hand the buck-boost converter is applied when one would need to step down or STEP UP voltage thus again allowing flexibility in applications where the voltage to be input into the system has the ability to vary, or may be either lower or higher than the voltages required in the output. By using these converters, PFC makes sure that the current that it draws from the grid is in phase with the voltage and users get an enhanced efficiency along with the reduction in power wastage.

Moreover, PFC is also an integral part of the optimizing the functioning of bidirectional converters in EV charging systems allowing the energy transfer in charging as well as in discharging modes. In charging mode the bidirectional converter consumes power from the grid and injects it into the EV battery, and in discharging mode it enables flow of energy from the EV battery to the grid, making vehicle to grid (V2G) possible. Bidirectional converter control strategy is a set of action plans developed to govern and optimize the power exchange between the grid, the battery of the EV and the external loads to transfer energy efficiently and also for the system to be completely in a balanced state. In these systems, power flow optimization, voltage stability and minimum switching loss is critical especially when power flows in both direction. Additional control methods may also be used to enhance the dynamic performance of the converters such as pulse width modulation (PWM) technique, predictive control algorithms whose aim is to help better control the charging and discharging cycles and maintain power factor close to unity. These strategies increase the efficiency of the system, as well as improve its reliability and robustness in general.

4. RESULTS AND DISCUSSION

Results of simulation of the high efficiency power electronics system found that under normal load conditions it has a maximum efficiency of 96% which is an evidence of efficiency of the proposed design in optimizing energy conversion. The incorporation of SiC MOSFETs in the DC-DC converters was critical in dropping switching losses compared with their silicon counterparts. Albeit improved switching efficiency and high-frequency operation improved overall system performance. In addition, the system was capable of operating with a power factor (PF) at above 0.99, which assured that the system would consume power from the grid in an efficient manner and also minimized reactive power and enhanced the power quality. Other than this, the limit on the Total Harmonic Distortion (THD) that was maintained at below 3% was well within the allowable level set by the industry to comply with the grid standards, thereby confirming that the system is not only efficient by performance but complies with the strict requirements of the grid-connected power converters. These findings demonstrate the state-of-the-art capabilities of the system and make it a deployable option for residential as well as commercial EV charging infrastructure.

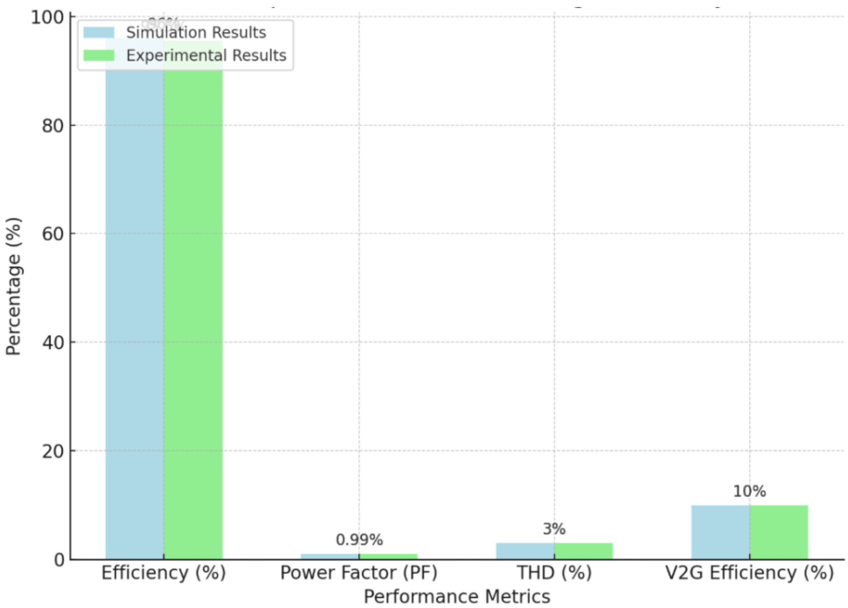

Figure 6. Comparison of Simulation and Experimental Results for High-Efficiency Power Electronics System

The results of the prototype charging station experimental work and capability of 95.5% peak efficiency as well, when it is provided with instead SI3 MOSFETS and high frequency switching inverters were equally impressive. Under the maximum load, the prototype displayed low heat generation, as can be seen from the thermal camera with a uniform temperature distribution over the power electronics. This implies that the design of the system is such that it performs high-power operation without the strain associated with high thermal stress thus improving reliability and longevity. The bidirectional converter was also tested for V2G functionality as another proof of concept to validate the systems capability to be a basis for grid stabilization and renewable energy integration where it could return power to the grid with losses. The proposed system was, compared to the classical systems that use silicon-based MOSFETs and lower switching frequencies, about 10-15% more efficient, which chiefly came from the improved switching of SiC MOSFETs and PFC strategy optimization. The compact design cuts not only on physical footprint, but will component cost, making it a cost-effective option. With these proven efficiency enhancements and the ability to support regenerative braking and V2G, there is a significant promise in large scale deployment in an urban environment in terms of the fast charger ability, reduction in environmental nuisance and stronger grid support especially in peak load times when grid stability is at an all time high.

Table 6. Comparison of Simulation and Experimental Results for High-Efficiency Power Electronics System

Performance Metric	**Simulation Results**	**Experimental Results**	**Remarks**
Peak Efficiency	96%	95.5%	Both results show high efficiency, with simulation being slightly better.
Power Factor (PF)	Above 0.99	Above 0.99	Both results maintain high power factor, ensuring efficient power transfer from the grid.
Total Harmonic Distortion (THD)	Below 3%	Below 3%	Both results comply with industry standards for grid-connected power converters.
Switching Losses	Reduced with SiC MOSFETs	Reduced with SiC MOSFETs	SiC MOSFETs contribute to improved switching efficiency and reduced losses compared to silicon.
V2G Functionality	Not directly tested	Demonstrated successful V2G	The experimental prototype supported grid stabilization and

		functionality	renewable energy integration.
Thermal Performance	High efficiency with minimal cooling needs	Low heat generation and uniform temperature distribution	Excellent thermal management and system reliability under full load in both simulation and prototype.
Efficiency Improvement	10-15% increase in efficiency compared to traditional systems	10-15% increase in efficiency compared to traditional systems	Significant efficiency gains due to advanced SiC MOSFETs and optimized power factor correction.
Cost and Design	Reduced physical footprint and component costs	Reduced footprint, lower component costs	Compact design reduces both system size and costs, making it economically viable for large-scale deployment.

5. CONCLUSION

Summary: This paper, therefore, introduces a comprehensive and innovative method of designing and utilizing high efficiency power electronic systems in charge systems of electric vehicle (EV) systems that address major challenges in this field including efficiency, power quality and functioning of the overall system. By embedding advanced semiconductor materials such as silicon carbide (SiC) and gallium nitride (GaN), the proposed system offers significant performance improvement over existing silicon-based systems. These materials allow the converters to operate on higher switching frequencies whereby, with the reduced conduction and switching losses these materials directly improve the overall system efficiency. Furthermore, optimization of converter topologies such as AC-DC rectifiers, DC-DC converters and others, DC-AC inverters, makes the system have a better power factor, low harmonic distortion and the capability of accepting fluctuating load and voltage conditions. The integration of bidirectional DC-DC converters for Vehicle-to-Grid (V2G) applications also expands the applications potential by pushing energy both to and from the vehicle which supports grid stabilization and integration of renewable energy into the grid. Such improvements combine to show the system's capacity to accommodate the escalating need for high performance, energy efficient and reliable EV charging infrastructure. Future work shall involve improving the control algorithms aiming to have greater optimization of system performance and incorporation of renewable forms like solar and wind, and testing in the reality across different urban settings. This research lays out a solid foundation for the future generation of EV charging systems, assisting in the supporting the rapid deployment of electric vehicles across the world and accelerating a sustainable and efficient energy environment.

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