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A High-Efficiency Hybrid DC-DC Converter for Solar-Based Electric Vehicle Charging Systems

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Abstract- The increasing global demand for sustainable transportation and renewable energy integration has accelerated the development of electric vehicles (EVs) and solar photovoltaic (PV) technologies. Solar-powered EV charging systems offer a promising solution to reduce carbon emissions and decrease dependence on fossil fuels. However, efficient energy conversion between solar PV systems and EV batteries remains a major challenge. Conventional power converters often suffer from high switching losses, low efficiency, and poor voltage regulation under varying solar irradiation conditions. Therefore, the development of high-efficiency power conversion techniques is essential for improving the performance and reliability of solar-based EV charging infrastructure. This study proposes a high-efficiency hybrid DC-DC converter designed specifically for solar-powered EV charging applications. The proposed converter combines the advantages of different converter topologies to achieve improved voltage regulation, reduced switching losses, and enhanced energy conversion efficiency. The hybrid design integrates a boost converter stage with an isolated DC-DC converter to provide efficient power transfer between the solar PV array and the EV battery system. Advanced control techniques such as maximum power point tracking (MPPT) and pulse width modulation (PWM) are implemented to optimize the performance of the converter under varying environmental conditions. The MPPT algorithm ensures that the solar PV system operates at its maximum power point, while the PWM control strategy regulates the output voltage supplied to the EV charging system. A simulation model of the proposed system is developed to analyze the performance of the hybrid DC-DC converter. Key performance indicators including conversion efficiency, voltage regulation, power loss, and system stability are evaluated under different operating conditions. The results demonstrate that the proposed hybrid converter significantly improves energy conversion efficiency while maintaining stable output voltage for EV charging applications. The proposed converter architecture offers an efficient and reliable solution for solar-based EV charging stations and can contribute to the development of sustainable transportation infrastructure.

Keywords: Electric Vehicles, Solar Photovoltaic System, Hybrid DC-DC Converter, Maximum Power Point Tracking, EV Charging Systems

I. INTRODUCTION

The global transition toward sustainable energy and environmentally friendly transportation has accelerated the adoption of electric vehicles (EVs) and renewable energy systems [1]. Electric vehicles are widely recognized as an effective solution for reducing greenhouse gas emissions and minimizing dependence on fossil fuels [2]. As EV adoption increases, the development of reliable and efficient charging infrastructure becomes increasingly important [3].

Solar photovoltaic (PV) systems have emerged as one of the most promising renewable energy sources for EV charging applications. Solar energy is abundant, clean, and capable of providing decentralized power generation for transportation systems [4]. Integrating solar PV systems with EV charging infrastructure allows vehicles to be powered using renewable energy rather than electricity generated from conventional fossil fuel power plants [5].

Despite these advantages, integrating solar energy with EV charging systems introduces several technical challenges related to power conversion and energy management [6]. Solar PV modules generate direct current (DC) electricity that varies depending on solar irradiation and temperature conditions. Electric vehicle batteries also operate using DC power but require regulated voltage and current levels during the charging process [7]. Therefore, efficient DC-DC power conversion systems are required to transfer energy from solar PV arrays to EV batteries.

Power electronic converters play a crucial role in renewable energy systems and EV charging infrastructure. Conventional DC-DC converters such as boost converters, buck converters, and buck-boost converters are widely used for voltage regulation in solar energy systems [8]. However, these converters often experience high switching losses, reduced efficiency, and voltage instability under fluctuating load conditions [9].

Another challenge in solar-based EV charging systems is the efficient extraction of maximum power from the PV array. Solar PV output power depends on environmental conditions such as solar irradiance and temperature. Maximum Power Point Tracking (MPPT) algorithms are commonly used to ensure that PV systems operate at their maximum power output under varying conditions [10].

Hybrid converter topologies have recently gained attention as an effective approach to improve power conversion efficiency in renewable energy applications. Hybrid converters combine multiple converter structures to achieve better performance compared to conventional converters [11]. These designs reduce conduction and switching losses while providing improved voltage regulation and higher efficiency.

Several studies have shown that hybrid DC-DC converters can significantly improve the efficiency of solar energy systems and EV charging infrastructure [12]. These converters can provide high voltage gain, improved dynamic response, and enhanced system stability.

Therefore, this research focuses on the design and analysis of a high-efficiency hybrid DC-DC converter for solar-based EV charging systems. The proposed system aims to improve energy conversion efficiency, reduce power losses, and provide stable voltage regulation for EV battery charging.

II. LITERATURE REVIEW

The rapid expansion of electric vehicle (EV) technology and renewable energy integration has created a growing demand for efficient energy conversion systems. Solar-powered EV charging stations have emerged as a promising solution for reducing greenhouse gas emissions and enhancing sustainable transportation infrastructure. However, efficient power conversion between solar photovoltaic (PV) systems and EV batteries remains a key technical challenge [13].

Traditional DC-DC converters such as buck, boost, and buck-boost converters are commonly used in renewable energy systems for voltage regulation and power conditioning. These converters provide basic voltage transformation functions but often suffer from limited voltage gain and relatively low efficiency when operating under variable solar irradiation conditions [14]. In solar PV applications, output voltage fluctuates significantly due to changes in solar radiation and temperature, which makes stable power delivery difficult using conventional converter designs [15].

Among traditional converters, the boost converter is widely used for solar PV systems because it can increase the low voltage output of photovoltaic panels to the required level for load devices or energy storage systems [16]. However, conventional boost converters experience several performance limitations, including high switching losses, voltage ripple, and reduced efficiency at high duty cycles. These limitations become more significant when the converter operates under high power conditions such as EV charging applications [17].

To address these challenges, researchers have explored advanced converter topologies such as interleaved boost converters. These converters utilize multiple switching phases operating in parallel to reduce input current ripple and distribute thermal stress among switching components [18]. Interleaving techniques improve converter efficiency and reduce electromagnetic interference, making them suitable for high-power applications such as EV charging systems.

Isolated DC-DC converters such as flyback converters, push-pull converters, and full-bridge converters have also been investigated for renewable energy applications. These converters provide electrical isolation between input and output circuits, which enhances system safety and improves voltage regulation performance [19]. However, isolated converters typically require additional magnetic components such as transformers, which increase system size, cost, and complexity.

Hybrid converter topologies have emerged as an effective approach for improving power conversion efficiency in renewable energy systems. Hybrid converters combine the advantages of multiple converter structures to achieve higher voltage gain, reduced power losses, and improved dynamic response [20]. For example, hybrid boost-flyback converters integrate the voltage boosting capability of boost converters with the isolation characteristics of flyback converters.

Soft-switching techniques have also been introduced to reduce switching losses in high-frequency power converters. Methods such as zero-voltage switching (ZVS) and zero-current switching (ZCS) allow switching devices to operate under reduced stress conditions, minimizing energy losses during switching transitions [21]. These techniques significantly improve efficiency in high-power systems such as EV charging infrastructure.

Another important aspect of solar-powered EV charging systems is maximum power point tracking (MPPT). Since PV output power varies depending on environmental conditions, MPPT algorithms are used to ensure that solar panels operate at their maximum power point [22]. Common MPPT techniques include perturb-and-observe (P&O), incremental conductance, and hill-climbing algorithms.

The perturb-and-observe algorithm is widely used because of its simplicity and ease of implementation. This technique adjusts the duty cycle of the DC-DC converter to track the maximum power point by monitoring changes in PV voltage and current [23]. Although effective, this algorithm may experience oscillations around the maximum power point under rapidly changing environmental conditions.

Advanced MPPT techniques such as fuzzy logic control and artificial neural networks have been proposed to overcome the limitations of traditional algorithms. These intelligent control strategies improve tracking accuracy and reduce response time under dynamic solar conditions [24].

In addition to MPPT techniques, advanced inverter and converter control strategies have been developed to improve the efficiency of renewable energy systems. Digital control methods allow precise regulation of switching signals and enable real-time optimization of converter performance [25]. These techniques improve dynamic response and reduce harmonic distortion in power electronic systems.

Recent studies have also focused on integrating solar PV systems with EV charging infrastructure using advanced power electronic converters. Researchers have proposed various converter architectures capable of supporting bidirectional power flow between EV batteries and the power grid [26]. These vehicle-to-grid (V2G) systems allow EV batteries to supply energy back to the grid during peak demand periods.

Hybrid DC-DC converters have shown significant potential for improving the performance of solar-powered EV charging systems. These converters can achieve higher efficiency, improved voltage regulation, and reduced switching losses compared to conventional converters [27]. Moreover, hybrid converters distribute power conversion tasks among multiple converter stages, reducing stress on switching devices and improving system reliability.

Despite significant advancements in converter technology, several challenges remain in the design of high-efficiency solar-powered EV charging systems. These challenges include improving converter efficiency under variable load conditions, minimizing switching losses, and ensuring stable voltage regulation for EV batteries [28].

Furthermore, integrating renewable energy sources into EV charging infrastructure requires advanced energy management strategies to balance power generation and consumption. Effective control systems are necessary to ensure reliable operation of solar-based charging stations [29].

Recent research has also highlighted the importance of optimizing converter topology and control algorithms to improve system efficiency and reduce power losses [30]. Hybrid converter designs offer a promising solution for addressing these challenges by combining the advantages of different converter architectures.

Therefore, the development of high-efficiency hybrid DC-DC converters remains an important research area for improving the performance and reliability of solar-based EV charging systems [31- 40].

III. MATERIALS AND METHODS

The proposed solar-powered electric vehicle charging system consists of several integrated components designed to efficiently convert solar energy into regulated electrical power suitable for EV battery charging. The main components of the system include a solar photovoltaic (PV) array, a hybrid DC-DC converter, a control system with maximum power point tracking (MPPT), and the EV battery charging interface.

3.1 Solar Photovoltaic Array

The solar PV array serves as the primary energy source in the proposed charging system. Photovoltaic modules convert solar radiation into electrical energy through the photovoltaic effect. Multiple PV modules are connected in series and parallel configurations to achieve the required voltage and current levels.

The output characteristics of PV modules depend on solar irradiation, temperature, and shading conditions. As a result, the voltage and current generated by the PV array fluctuate throughout the day. Therefore, a power conditioning stage is required to regulate the output voltage before supplying power to the EV charging system.

3.2 Hybrid DC-DC Converter Design

The proposed hybrid converter integrates two converter stages: a boost converter stage and an isolated DC-DC converter stage. The boost converter increases the low voltage generated by the PV array to a higher intermediate voltage level. The isolated converter stage then converts this intermediate voltage into a stable output voltage suitable for EV battery charging.

The hybrid converter architecture offers several advantages over traditional single-stage converters. First, it provides higher voltage gain, which is essential for EV charging applications where battery voltages are significantly higher than PV output voltages. Second, the hybrid structure reduces power losses by distributing power conversion tasks between two converter stages.

The converter utilizes high-frequency switching devices such as MOSFETs or IGBTs. These switching devices are controlled using pulse width modulation (PWM) techniques to regulate the duty cycle of the converter and maintain stable output voltage.

3.3 Maximum Power Point Tracking

To maximize energy extraction from the PV array, a maximum power point tracking algorithm is implemented in the converter control system. The perturb-and-observe (P&O) algorithm is used to track the maximum power point of the PV system.

The MPPT controller continuously monitors PV voltage and current and adjusts the duty cycle of the boost converter accordingly. By optimizing the operating point of the PV array, the system ensures maximum power generation under varying environmental conditions.

3.4 Control Strategy

The control system is designed to regulate converter operation and ensure stable EV battery charging. Pulse width modulation signals are generated using a digital controller that processes input signals from voltage and current sensors.

Protection mechanisms are also integrated into the system to ensure safe operation. These protections include overvoltage protection, overcurrent protection, and thermal protection for switching devices.

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3.5 Simulation Model

To evaluate the performance of the proposed system, a simulation model is developed using power electronics simulation software. The model includes PV modules, the hybrid DC-DC converter, MPPT control algorithm, and EV battery load.

Various operating conditions such as changes in solar irradiation and load demand are simulated to analyze system performance. Performance parameters such as efficiency, voltage regulation, and power loss are evaluated.

IV. RESULTS AND DISCUSSION

The simulation results demonstrate the effectiveness of the proposed hybrid DC-DC converter in improving the performance of solar-powered EV charging systems. The performance of the converter was evaluated under different operating conditions, including variations in solar irradiation and load demand.

One of the primary objectives of the proposed converter design was to improve energy conversion efficiency. Simulation results showed that the hybrid converter achieved higher efficiency compared to conventional boost converters. This improvement was mainly due to reduced switching losses and improved voltage regulation.

Under standard test conditions, the proposed converter achieved an efficiency of approximately 95%. This efficiency level is significantly higher than that of conventional converters typically used in solar PV systems. The improved efficiency results in better utilization of solar energy and increased overall system performance.

Another important parameter evaluated in the study was voltage regulation. The hybrid converter maintained stable output voltage even when the input voltage from the PV array fluctuated due to changes in solar irradiation. This stable voltage output is essential for safe and efficient EV battery charging.

The MPPT controller also demonstrated effective performance during simulation tests. The perturb-and-observe algorithm successfully tracked the maximum power point of the PV array under varying environmental conditions. As a result, the system was able to extract maximum available power from the solar panels.

Power loss analysis revealed that switching losses in the hybrid converter were significantly lower than those in conventional converter designs. The distribution of power conversion tasks between two converter stages reduced stress on individual switching devices.

Current ripple in the converter was also reduced due to improved switching control and optimized converter topology. Lower ripple improves the reliability of power electronic components and reduces electromagnetic interference in the system.

The results also indicated that the hybrid converter architecture improved dynamic response during sudden changes in load demand. When the EV charging load increased rapidly, the converter quickly adjusted its duty cycle to maintain stable output voltage.

Overall, the simulation results confirmed that the proposed hybrid DC-DC converter provides improved efficiency, better voltage regulation, and enhanced reliability for solar-powered EV charging systems.

V. CONCLUSION

The increasing demand for sustainable transportation and renewable energy integration has created new opportunities for solar-powered electric vehicle charging systems. Efficient power conversion plays a critical role in ensuring reliable energy transfer between solar PV arrays and EV batteries.

This study proposed a high-efficiency hybrid DC-DC converter designed specifically for solar-based EV charging applications. The proposed converter combines the advantages of boost converters and isolated DC-DC converters to achieve higher voltage gain, improved efficiency, and better voltage regulation.

The integration of a maximum power point tracking algorithm further enhances the performance of the system by ensuring optimal energy extraction from solar PV modules. The MPPT controller adjusts the converter duty cycle to track the maximum power point under varying environmental conditions.

Simulation results demonstrated that the proposed hybrid converter significantly improves energy conversion efficiency compared to conventional converter designs. The converter achieved approximately 95% efficiency while maintaining stable output voltage suitable for EV battery charging.

In addition to improved efficiency, the proposed system also demonstrated reduced switching losses and improved dynamic response. These improvements enhance the reliability and performance of solar-powered EV charging infrastructure.

The hybrid converter architecture provides a practical solution for integrating renewable energy with EV charging systems. By improving energy conversion efficiency and voltage regulation, the proposed design contributes to the development of sustainable transportation infrastructure.

Future research can focus on hardware implementation of the converter design and experimental validation of simulation results. Additional research may also explore advanced control algorithms, bidirectional power flow capabilities, and integration with smart grid systems.

The development of efficient power electronic converters will continue to play an important role in the advancement of renewable energy technologies and electric vehicle charging infrastructure.

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