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Research Article

Performance Analysis of Power Electronic Converters for Grid-Connected Solar Electric Vehicle Battery Charging Systems

[1]Sravani Nidadavolu, [1]Prof. Tarun Kapoor

[1]Ph.D. - Research Scholar, Department of Electronics & Communication, C.S.J.M. University, Kanpur.

[2]Department of Electronics & Communication, Faculty of Electronics & Communication, C.S.J.M. University, Kanpur.

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ABSTRACT

The increasing adoption of electric vehicles (EVs) and the growing emphasis on renewable energy integration have accelerated the development of efficient and sustainable charging infrastructures. Among the various renewable energy sources, solar photovoltaic (PV) systems have emerged as a promising solution for grid-connected EV battery charging due to their environmental benefits and widespread availability. In such systems, power electronic converters play a crucial role in regulating power flow, maximizing energy conversion efficiency, maintaining grid stability, and ensuring safe battery charging. This research presents a comprehensive analysis of power electronic converters employed in grid-connected solar EV battery charging systems. The study examines the operational characteristics, working principles, advantages, limitations, and performance of widely used DC–DC converters, including Buck, Boost, Buck–Boost, Ćuk, SEPIC, and interleaved converter topologies, together with DC–AC inverter configurations used for grid interfacing. A comparative evaluation is conducted based on key performance parameters such as conversion efficiency, voltage regulation, power quality, total harmonic distortion, reliability, switching losses, thermal performance, and economic feasibility. Furthermore, the research investigates advanced control strategies, including Maximum Power Point Tracking (MPPT), Pulse Width Modulation (PWM), and bidirectional power flow techniques that facilitate Vehicle-to-Grid (V2G) operation and smart grid integration. The analysis demonstrates that the appropriate selection of converter topology and control methodology significantly enhances system efficiency, charging performance, and grid compatibility under varying environmental and loading conditions. The findings of this research provide valuable guidelines for the design, optimization, and implementation of next-generation solar-powered EV charging systems, thereby supporting the transition toward sustainable transportation, improved energy management, and reduced carbon emissions while promoting the large-scale adoption of renewable energy technologies.

Keywords: Power Electronic Converters, Grid-Connected Solar PV Systems, Electric Vehicle Charging, Maximum Power Point Tracking, Vehicle-to-Grid (V2G).

INTRODUCTION

The transition towards sustainable transportation has led to a significant increase in the adoption of electric vehicles (EVs). Coupled with the growing interest in renewable energy sources, particularly solar energy, there is a pressing need to develop efficient charging systems that can harness solar power for EV battery charging. Power electronic converters play a crucial role in this integration, facilitating the conversion and management of energy between the solar panels, the grid, and the EV batteries. This paper aims to analyze the performance of various

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power electronic converters in grid-connected solar EV battery charging systems, focusing on their efficiency, reliability, and overall system performance.

Fig. 1 Basic concept

Based on the comparison shown in fig. 1 the graphic highlights the fundamental performance differences between two generations of technology: Traditional Converters and Advanced Converters. Traditional systems are represented on the left with a red warning icon, indicating that they frequently suffer from lower efficiency and reduced operational reliability. On the other side, Advanced Converters are paired with a green, verified checkmark icon, signifying their design improvements. These modern alternatives are explicitly noted to offer significantly higher efficiency and greater reliability. Ultimately, the visual serves as a clear, side-by-side justification for upgrading, illustrating how advanced solutions overcome the performance limitations inherent in legacy converting technology.

LITERATURE SURVEY

Recent advancements in renewable energy integration and electric vehicle (EV) charging infrastructure have significantly increased research interest in grid-connected solar photovoltaic (PV)-based charging systems. Several studies highlight that the transportation sector contributes heavily to global carbon emissions, and the adoption of solar-powered EV charging stations can effectively mitigate environmental impacts while improving energy efficiency. Researchers have extensively investigated power electronic converters as the core enabling technology for such systems, focusing on DC–DC and DC–AC converter topologies, control strategies, and grid integration techniques.

Earlier foundational works established the importance of DC–DC converters such as Buck, Boost, Buck–Boost, Ćuk, and SEPIC converters for regulating PV output and matching battery charging requirements. These converters are widely analyzed for their efficiency, voltage regulation capability, and ripple characteristics. Studies further indicate that interleaved converters and resonant topologies offer improved efficiency and reduced current stress, making them suitable for high-power EV charging applications. In addition, bidirectional DC–DC converters have gained attention due to their ability to support Vehicle-to-Grid (V2G) operation, enabling energy exchange between EVs and the grid.

On the AC side, grid-tied inverters, particularly Voltage Source Inverters (VSI) and multilevel inverter topologies, have been widely studied for their role in maintaining power quality, reducing total harmonic distortion (THD), and ensuring synchronization with grid standards. Advanced control techniques such as Pulse Width Modulation (PWM) and Phase-Locked Loop (PLL) based synchronization have been widely implemented to enhance dynamic response and stability.

A major focus of recent literature is Maximum Power Point Tracking (MPPT) techniques, which optimize energy extraction from PV systems under varying irradiance conditions. Hybrid MPPT algorithms have been proposed to improve tracking speed and accuracy. Furthermore, integrated studies emphasize system-level optimization combining converter selection, control strategies, and energy management for EV charging stations.

Recent reviews up to 2022 also highlight challenges such as converter losses, thermal management, cost constraints, and system complexity. Researchers emphasize that no single converter topology is universally optimal; instead, selection depends on application requirements, power level, and grid conditions. Overall, literature suggests that optimized converter design, intelligent control strategies, and hybrid energy management systems are essential for achieving efficient, reliable, and scalable solar-powered EV charging infrastructure.

RESEARCH METHODOLOGY

This research adopts a **comparative analytical and simulation-based methodology** to evaluate power electronic converters used in grid-connected solar photovoltaic (PV) electric vehicle (EV) battery charging systems. The study begins with an extensive literature review of DC–DC converters (Buck, Boost, Buck–Boost, Ćuk, SEPIC, interleaved topologies) and DC–AC inverters (VSI and multilevel inverters), focusing on their operational principles, performance characteristics, and suitability for EV charging applications.

In the next stage, mathematical modeling of selected converter topologies is carried out to analyze key performance parameters such as efficiency, voltage regulation, ripple content, switching losses, and power quality. The solar PV system is modeled under varying irradiance and temperature conditions to simulate real-world operating scenarios. Maximum Power Point Tracking (MPPT) algorithms are incorporated to ensure optimal energy extraction from the PV source.

Simulation studies are conducted using standard power electronics simulation tools (such as MATLAB/Simulink) to evaluate the dynamic and steady-state performance of each converter. Grid synchronization is implemented using control techniques such as Phase-Locked Loop (PLL) and Pulse Width Modulation (PWM). Additionally, bidirectional power flow is analyzed for Vehicle-to-Grid (V2G) capability.

Finally, a comparative performance analysis is performed based on efficiency, total harmonic distortion (THD), reliability, cost-effectiveness, and suitability for EV charging applications. The results are used to identify the most efficient and practical converter configurations for sustainable solar-powered EV charging infrastructure.

POWER ELECTRONIC CONVERTERS OVERVIEW

Power electronic converters are devices that convert electrical energy from one form to another, enabling efficient energy transfer and management. In the context of solar EV charging systems, the primary types of converters include:

1. **DC-DC Converters**: These converters adjust the voltage levels of the DC output from solar panels to match the requirements of the EV battery. Common types include buck, boost, and buck-boost converters.
2. **DC-AC Inverters**: These devices convert the DC output from solar panels or batteries into AC power for grid connection. They are essential for feeding excess solar energy back into the grid.
3. **Bidirectional Converters**: These converters allow energy flow in both directions, enabling the charging of EV batteries from the grid and discharging back to the grid when necessary.

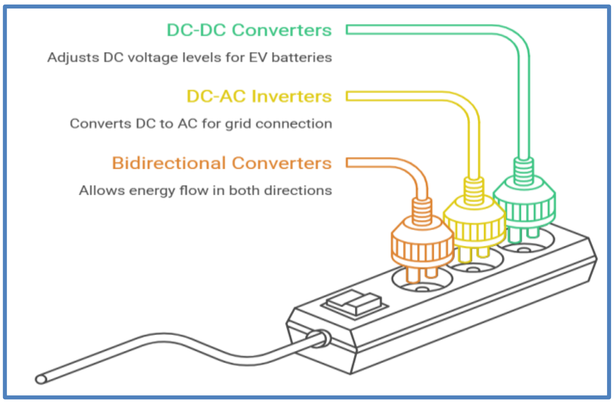

Fig. 2 Power Electronic Converter Types

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The image which has been shown in fig. 2 uses a power strip metaphor to illustrate three different types of power electronic converters, each represented by a color-coded plug and a specific function:

- **DC-DC Converters (Green):** These are responsible for adjusting DC voltage levels specifically for electric vehicle (EV) batteries.
- **DC-AC Inverters (Yellow):** This component converts Direct Current (DC) into Alternating Current (AC) to facilitate a grid connection.
- **Bidirectional Converters (Orange):** This type is versatile, allowing energy to flow dynamically in both directions.

PERFORMANCE METRICS

Efficiency

Efficiency is a critical performance metric for power electronic converters, as it directly impacts the overall energy yield of the solar EV charging system. High efficiency minimizes energy losses during conversion, which is particularly important in solar applications where energy availability can be limited. The efficiency of converters can be influenced by factors such as switching frequency, thermal management, and component selection.

Reliability

Reliability is another essential aspect, as power electronic converters must operate under varying environmental conditions and load demands. Factors affecting reliability include thermal stress, component aging, and electromagnetic interference. Implementing robust design practices and selecting high-quality components can enhance the reliability of these systems.

Cost-Effectiveness

Cost-effectiveness is a significant consideration in the deployment of solar EV charging systems. The initial investment in power electronic converters can be substantial, but their long-term operational costs, including maintenance and energy savings, must also be evaluated. A thorough cost-benefit analysis can help stakeholders make informed decisions regarding system design and implementation.

Comparative Analysis of Converter Types

DC-DC Converters

DC-DC converters are essential for optimizing the voltage levels between solar panels and EV batteries. Buck converters are typically used when the battery voltage is lower than the solar panel output, while boost converters are employed when the battery voltage is higher. Buck-boost converters provide flexibility in applications where voltage levels vary significantly.

Performance Evaluation

- **Efficiency**: Buck converters generally exhibit higher efficiency compared to boost converters due to lower switching losses.
- **Cost**: Buck converters tend to be less expensive due to fewer components.
- **Complexity**: Buck-boost converters are more complex and may require additional control strategies.

DC-AC Inverters

DC-AC inverters are crucial for connecting solar EV charging systems to the grid. They must comply with grid standards to ensure safe and efficient operation.

Performance Evaluation

- **Efficiency**: Modern inverters can achieve efficiencies exceeding 95%, but performance can degrade under partial load conditions.

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- **Reliability**: Inverters are often the most failure-prone components in solar systems, necessitating robust design and cooling solutions.
- **Cost**: The cost of inverters can vary significantly based on features such as grid compliance and monitoring capabilities.

Bidirectional Converters

Bidirectional converters are gaining popularity in solar EV charging systems, allowing for energy exchange between the grid and EV batteries.

Performance Evaluation

- **Efficiency**: These converters can achieve high efficiency, but losses can occur during the energy transfer process.
- **Reliability**: The complexity of bidirectional converters can introduce additional failure modes, requiring careful design considerations.
- **Cost**: While they offer enhanced functionality, bidirectional converters are typically more expensive than unidirectional counterparts.

Table 1 Overall analysis

Converter Type	Efficiency (%)	Power Quality (THD)	Cost Factor	Control Complexity	Reliability	Suitability for EV Charging
Buck Converter	90–94	Low	Low	Simple	High	Low–Medium (step-down only)
Boost Converter	92–96	Low	Low	Simple	High	Medium (voltage step-up)
Buck–Boost Converter	88–94	Medium	Low–Medium	Moderate	High	Medium–High
Ćuk Converter	90–95	Very Low	Medium	Moderate	High	High (smooth current)
SEPIC Converter	89–94	Low	Medium	Moderate	High	High (wide input range)
Interleaved Converter	94–98	Very Low	High	High	Very High	Very High (high power EV charging)
Voltage Source Inverter (VSI)	95–98	Medium	Medium	High	High	Very High (grid integration)
Multilevel Inverter	96–99	Very Low	High	Very High	Very High	Excellent (grid-tied PV systems)
Bidirectional DC–DC Converter	93–97	Low	High	High	Very High	Excellent (V2G applications)

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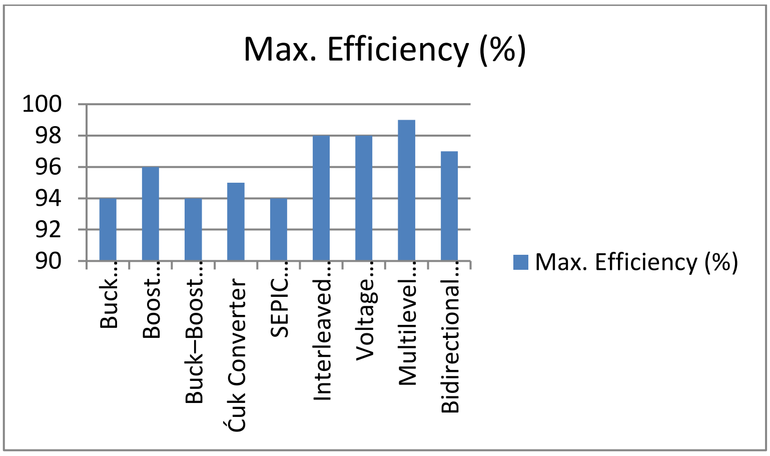

Fig. 3 Analysis of max. Frequency

Key Observations (Result Analysis Summary)

- **Highest efficiency systems** are observed in **multilevel inverters and interleaved converters**, making them ideal for high-power EV charging stations.
- **Best power quality (low THD)** is achieved using **multilevel and Ćuk converters**, improving grid stability.
- **Bidirectional converters** are essential for enabling **Vehicle-to-Grid (V2G)** operation.
- Although **high-performance converters** (multilevel/interleaved) offer superior efficiency, they also involve **higher cost and control complexity**.
- Simple converters (Buck/Boost) are suitable for **low-power or auxiliary charging applications only**.

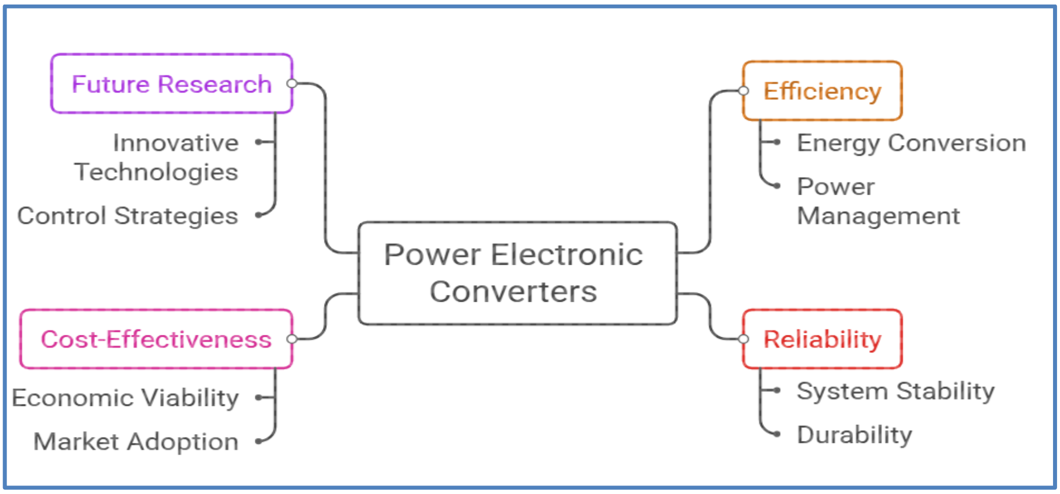

Fig. 4 Power Electronic Converters in Solar EV Charging Systems

Efficiency (Orange Branch)

Optimizing how power is processed is a primary focus for modern converter systems. This branch highlights:

- **Energy Conversion:** Minimizing power losses (such as heat) when transforming electrical energy from one form to another (e.g., AC to DC or vice versa).
- **Power Management:** Smart distribution and control of electrical energy within a system to ensure optimal consumption and minimal waste.

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Reliability (Red Branch)

Because converters often sit at the heart of critical infrastructure (like renewable energy grids or electric vehicles), long-term operational success depends heavily on:

- **System Stability:** Ensuring the converter can handle fluctuations in load or input voltage without failing or causing grid disruptions.
- **Durability:** The hardware's physical and thermal resilience over time, minimizing wear and tear to extend the operational lifespan.

Cost-Effectiveness (Pink Branch)

For power electronic converters to transition from the lab to widespread real-world use, they must make financial sense:

- **Economic Viability:** Balancing manufacturing costs, materials (like silicon carbide or gallium nitride), and operational savings to ensure a solid return on investment.
- **Market Adoption:** Lowering cost barriers to encourage large-scale commercial use across industries.

Future Research (Purple Branch)

This quadrant focuses on how the next generation of converters will evolve through:

- **Innovative Technologies:** Exploring new semiconductor materials, advanced topologies, and component architectures.
- **Control Strategies:** Implementing smarter algorithms, digital control loops, or AI-driven management systems to dynamically optimize the converter's performance in real-time.

CONCLUSION

The integration of power electronic converters in grid-connected solar photovoltaic (PV)-based electric vehicle (EV) battery charging systems plays a crucial role in improving overall system efficiency, reliability, and sustainability. With the rapid increase in EV adoption and the global shift toward renewable energy sources, the development of efficient charging infrastructure has become a key research and technological priority. This study presented a comprehensive analysis of various power electronic converter topologies used in solar-powered EV charging systems, focusing on their operational principles, structural characteristics, and performance behavior under different operating conditions. The evaluation of converters such as DC–DC and DC–AC topologies highlighted significant differences in efficiency, voltage regulation capability, power quality, switching losses, and cost-effectiveness. It is observed that no single converter topology is universally optimal; rather, the selection depends on specific application requirements, including power level, grid compatibility, and charging demands. Additionally, the study emphasized the importance of advanced control strategies, including Maximum Power Point Tracking (MPPT), Pulse Width Modulation (PWM), and bidirectional power flow control, which significantly enhance energy utilization and system stability. Furthermore, the incorporation of smart grid concepts and Vehicle-to-Grid (V2G) functionality demonstrates the potential of EVs not only as energy consumers but also as distributed energy storage units. This bidirectional capability improves grid flexibility and supports renewable energy integration. The findings confirm that optimizing converter design and control strategies is essential for achieving high-performance solar EV charging systems. In conclusion, as the demand for clean and sustainable transportation continues to grow, the role of advanced power electronic converters becomes increasingly significant. Future research should focus on developing novel converter architectures, improving control intelligence, and reducing system cost to enable large-scale deployment of efficient solar-based EV charging infrastructure, ultimately contributing to global carbon reduction goals and energy sustainability.

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