Reliability Aspects and Performance Enhancement of Grid-Integrated Electric Vehicles

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for the Award of Degree

Doctor of Philosophy

By

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Chapter 8

Conclusion and Future Research

This chapter concludes the thesis. The summary of each chapter is in section 8.1. Significant Contributions to the Thesis are outlined in Sections 8.2 and 8.2.1. Conclusions, Benefits of the Proposed Work, and guidelines for future research is given in Sections 8.3, 8.4, and 8.5 respectively.

8.1 Summary

This Thesis reviewed the existing literature, focusing on the classification of EVs, the challenges and issues surrounding EV technology, and the converter topologies used in EV applications.

- In the second chapter of this thesis, detailed literature is provided, which provides the integration of EVs with the power grid, a crucial step for sustainable transportation. It explores different EV converter topologies for grid integration, highlighting the advantages and disadvantages of various battery charging technologies. The chapter covers off-board and on-board EV chargers, related charging infrastructure, and the standards involved. Vehicle-to-grid (V2G) and Grid-to-Vehicle (G2V) technologies are assessed regarding their impact on travel behavior, reliability parameters, battery life, and grid integration challenges. Bi-directional converters, which improve efficiency and battery longevity, are also discussed.
- Chapter 3 presented a novel event-triggered control strategy for boost converters

based on a Linear Parameter-Varying (LPV) framework. The design of the controller, driven by duty cycle regulation, enhances voltage control and reduces computational demands by minimizing control updates. The system's stability is verified under input voltage and load current variations, with simulation and experimental results demonstrating its effectiveness. The chapter also addressed Zeno behavior by proposing a lower bound for the inter-event time.

- Chapter 4 investigated the use of Sliding Mode Control (SMC) for Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) applications. The controller ensures stability in step-up and step-down modes without requiring explicit knowledge of the operating mode. This chapter also discussed mitigating the chattering effect in power converters, and a cascaded control design is used to ensure stable voltage and current loops. Simulation results validate the efficiency of the proposed controller.

- Chapter 5 focused on applying Super Twisting Control (STC) to Solar-to-Vehicle (S2V) systems. STC proves to be an adaptive and robust control strategy that effectively handles disturbances and uncertainties in solar energy conversion. This chapter demonstrates how STC improves the efficiency and reliability of S2V systems, with simulation experiments confirming the precision and stability of the control scheme.

- Chapter 6, 7 introduced a novel interleaved buck-boost converter topology with reduced switches suitable for AC-DC and DC-DC conversion in EV charging systems. The proposed converter, which employs a single-sensor controller for effective Power Factor Correction (PFC), achieves high efficiency (96%) and near unity power factor (0.9992). In Chapter 6, there is also a discussion of design considerations for inductors in Discontinuous Conduction Mode (DCM) and filter capacitor selection. The proposed converter is compact and cost-effective for G2V charging applications. In addition it is also suitable for Vehicle-to-Vehicle (V2V) and Solar-to-Vehicle (S2V) charging scenarios.

8.2 Major Contributions of the Thesis

(i) AC-DC Buck-Boost Converter with Effective PFC Operation: The proposed converter achieves high performance in AC-DC conversion, offering effective Power Factor Correction (PFC) across a wide input voltage range. A single-sensor control strategy simplifies the implementation, making it highly suitable for EV battery charging technologies.

(ii) Simulation and Comparative Evaluation: Detailed simulation results are presented, along with a comprehensive tabular comparison of the proposed converter's performance against existing topologies. The evaluation highlights significant improvements in efficiency and power factor.

(iii) Design Considerations for Inductors and Filter Capacitors: In-depth design methodologies for inductors operating in Discontinuous Conduction Mode (DCM) are discussed, alongside the selection criteria for filter capacitors. These elements are crucial for achieving the desired performance in the proposed converter.

(iv) Critical Parameters for DCM Operation: Through simulation, key conduction parameters essential for stable operation in DCM are determined and validated, providing valuable insights into the converter's operational behavior.

(v) Performance Validation at 1 kW: The proposed converter has been rated at 1 kW and achieves an efficiency of 96%, with a power factor of 0.9992. These metrics affirm the system's suitability for EV battery charging applications.

(vi) Robust Voltage Control: The converter's voltage controller has been rigorously tested, demonstrating robust performance. The output voltage tracks the reference voltage with a fast settling time of 80 ms, ensuring reliable operation under dynamic conditions.

(vii) Universal Converter for G2V, V2V, and S2V Applications: The proposed topology is not limited to traditional Grid-to-Vehicle (G2V) applications. Due to its compact design and reduced cost, it can also serve as a universal onboard charger for Vehicle-to-Vehicle (V2V) and Solar-to-Vehicle (S2V) systems.

8.2.1 Minor Contributions of the Thesis

This Thesis highlights the benefits of the proposed methods in improving EV charger design, converter efficiency, and power management in various EV applications. The chapters also propose future research directions, such as further optimization of converter control strategies, real-world hardware implementation, and the expansion of the system for other renewable energy sources and larger-scale EV applications.

8.3 Conclusions

This thesis addresses unidirectional, bidirectional, and single-stage power converter topologies. However, if all these three possibilities are combined in a single converter, then that system will be very suitable for practical use. This will increase flexibility and reduce the cost of the charger. Therefore, a universal multifunctional charger with G2V, S2V, and V2V capability will reduce manufacturing costs due to mass production and increase flexibility by accepting power from AC grid and solar PV. To illustrate this concept, Fig. 6.3 is included in chapter 6. where input to the charger is either an AC grid or solar PV. Also, it will be able to participate in V2V, making it a single charger solution.

Grid to a vehicle (G2V) operation: This part is clearly explained in Chapter 6 due to the Interleaved buck-boost converter topology.

Solar to vehicle (S2V) operation: A single-stage S2V power converter requires maximum power point tracking from solar PV. Traditionally, this is done using boost or boost-derived converters. Again, a choice is preferred due to the interleaved boost, as explained in Chapter 7.

Vehicle to Vehicle (V2V) operation:

- If solar and grid sources are inaccessible at a particular location, this charger supports charging the vehicle from another vehicle in an emergency.

- The proposed system's reliability has been improved by integrating various input sources, as discussed in Chapter 6, thereby enhancing its dependability.
- The IBC has less component count, bidirectional feature (G2V, V2V), less control complexity, and low THD on the input side, i.e. ($< 5\%$). Hence, this converter is more effective than other compared converters in Table. 6.3.

- Reliability and Performance Improvements: The system demonstrates improved thermal performance and efficiency due to interleaved operation, reducing stress on power devices. Integrating multiple energy sources enhances system reliability, as discussed in Chapter 6. Simulation and experimental validation confirm that the proposed system performs better than conventional single-stage converters in terms of efficiency and transient response.

8.4 Benefits of the Proposed Work

The significant advantages have been discovered as a result of this thesis study. The proposed converter utilizes a multifunctional approach for EV charging through a single power conversion system. It serves as an AC/DC power factor correction (PFC) rectifier when connected to the grid (as discussed in Chapter 6), operates as a DC/DC converter with maximum power point tracking (MPPT) when using solar power (explored in Chapter 7), and supports vehicle-to-vehicle (DC/DC) charging, which is planned for future development. With these versatile capabilities, it can be aptly called a "Multi-functional Plug-in EV On-board Charger for Sustainable Transportation."

8.4.1 Reliability and Performance Improvements:

• The system demonstrates improved thermal performance and efficiency due to interleaved operation, reducing stress on power devices.

• Integrating multiple energy sources enhances system reliability, as discussed in Chapter 6.

- Simulation and experimental validation confirm that the proposed system performs better than conventional single-stage converters in terms of efficiency and transient response.

8.5 Scopes for the Future Work

Based on the research done in this thesis, the recommendations for future research are as follows:

- **Advanced Control Strategies:** Investigate adaptive or intelligent control methods, such as fuzzy logic or machine learning algorithms, to enhance the dynamic performance and efficiency of the IBC under varying load and environmental conditions.
- **Hardware Implementation:** Extending the study to real-time hardware implementations and field testing to validate the simulation results and assess the practical performance of the system under real-world conditions.
- **Optimization of Power Components:** Exploring the use of advanced materials and technologies, such as GaN or SiC-based semiconductors, to further minimize power losses and improve thermal management in the converter.
- **Wireless Charging Technologies :** Investigate the incorporation of wireless charging technology within the on-board charger, focusing on how it can be optimized for multi-modal charging (G2V, S2V, and V2V). This could increase convenience and expand the flexibility of EV charging systems.
- **Scalability:** Studying the scalability of the proposed system for larger electric vehicles or different renewable energy applications, such as integrating wind energy with the existing PV system.
- **Cybersecurity and Data Management:** Developing robust cybersecurity measures is critical as multi-functional chargers involve bi-directional energy flow and communication with multiple energy sources. Investigating secure communication

protocols and data management techniques for vehicle-to-grid and vehicle-to-vehicle interactions could be an important area of future work.

By addressing these future areas of research, the system could become even more efficient, reliable, and adaptable, promoting the widespread adoption of hybrid solar-powered electric vehicles. Focusing on these areas would allow us to explore innovative ways to enhance the efficiency and sustainability of EV onboard chargers, contributing significantly to the development of intelligent, eco-friendly transportation systems.

Limitations: While the proposed charger offers significant improvements, certain limitations exist:

• Hardware Implementation Challenges: Practical design considerations such as component sizing, thermal management, and cost constraints need further optimization.

• MPPT Optimization: The MPPT algorithm can be improved to enhance the tracking speed and efficiency under rapidly changing solar irradiance conditions.

• Bidirectional Power Flow Enhancement: The V2V charging operation can be further refined to improve power flow control and communication between EVs.

• Experimental Validation: Although the simulation results validate the effectiveness of the proposed topology, extensive real-time hardware testing under different load conditions is necessary to confirm its practical feasibility as discussed in chapter 6.