

Optimal Control of Fast Charging Converters for Renewable Systems in E-Vehicle Applications

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Abstract. This review delves into the optimal control of fast charging converters for renewable systems in electric vehicle (EV) applications. With the rise of EVs, a robust charging infrastructure becomes imperative. Ultra-fast charging (UFC) technology emerges as a pivotal solution for medium to long-distance travels. One study introduces a smart charging station with a modular DC/DC design, distributing power across multiple charging ports. By modeling this as an optimization problem, the goal is to minimize charging time and cost, with simulations suggesting that 800 kW power can efficiently serve 10 charging spots. Another study highlights global EV technological progress, emphasizing diverse EV types and their energy management. The importance of optimizing power distribution among varied energy storage elements is discussed. The potential of wide bandgap (WBG) semiconductor technology, especially SiC devices in EVs, is underscored, detailing their characteristics and the significance of energy optimization for EV charging. Challenges with SiC modules are also explored, providing insights for future research.

1 Introduction

The Imperative of Electric Mobility and Charging Infrastructure

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The transition to electric vehicles (EVs) is not just a technological shift but a key component of global energy transition aimed at reducing greenhouse gas emissions and other environmental impacts. As EVs gain traction, the demand for Ultra-Fast Charging Stations (UFCS) is also on the rise, especially for long-medium distance travels. UFCS can alleviate range anxiety, a common concern among potential EV adopters. However, the availability of such charging facilities is still not widespread, despite significant investments from governments worldwide. This sets the stage for our review, which focuses on optimal control strategies for fast charging converters in renewable systems for EV applications.

The Complexity of Charging Infrastructure

The challenge of UFCS extends beyond mere availability. The diversity in battery specifications among different EV models complicates the optimal sizing of these stations and their individual charging points. For instance, a station designed with 120 kW chargers may not efficiently serve vehicles requiring lower or higher power levels. This leads to inefficiencies and constraints in serving multiple vehicles simultaneously. Our review ties into this by examining smart charging systems that employ modular DC/DC converters to distribute power optimally across multiple charging ports.

The Role of Advanced Power Electronics

Power electronics, particularly Wide Bandgap (WBG) semiconductor technology like Silicon Carbide (SiC), play a pivotal role in efficient energy conversion for EVs. SiC devices offer advantages such as reduced energy losses, higher switching frequencies, and better thermal performance compared to traditional silicon-based devices. However, they also present challenges like higher costs and design complexities. Our review explores the technological advancements in SiC devices, focusing on their application in EV charging systems to enhance efficiency and reduce charging time.

Energy Management and Storage Systems

Another layer of complexity in EV technology is the energy storage systems (ESS) like lithium-ion batteries, fuel cells, and super capacitors. These systems require efficient energy management strategies (EMS) to optimize power flow and improve the vehicle's overall efficiency. Our review also delves into this aspect, highlighting the importance of EMS in conjunction with advanced power electronics for a holistic approach to fast and efficient EV charging.

In summary, this review aims to provide a comprehensive understanding of the technological advancements and challenges in fast charging converters for renewable systems in EV applications. It seeks to bridge the gap between current practices and future needs, offering insights for researchers and policymakers alike.

2 Review and discussions

In a comprehensive study conducted by Leone.C et al. (2021), the burgeoning presence of electric vehicles (EVs) on global roadways has underscored the pressing need for a robust and efficient charging infrastructure [1]. Central to this research is the exploration of the nascent ultra-fast charging (UFC) technology. This innovative approach aspires to replicate the convenience and speed of traditional gasoline refuelling, thereby acting as a significant catalyst in encouraging a wider acceptance of EVs, particularly for those embarking on medium to long-distance journeys.

The research meticulously outlines a novel concept for a smart charging station. This station is characterised by its modular DC/DC stage design, which is ingeniously crafted to distribute output power across a multitude of charging ports. One of the pivotal challenges addressed in the study is the formulation and resolution of an optimization problem. The crux of this problem is to ascertain the ideal number of modular shared DC/DC converters that would guarantee both minimal charging durations and cost-efficiency.

Key Findings [3-8]:

- **Escalating Demand for Charging Infrastructure:** The surge in EV adoption has precipitated an urgent call for a comprehensive and efficient charging infrastructure. Ultra-Fast Charging Stations (UFCS) have emerged as indispensable, especially when catering to long-medium distance vehicular travels.
- **Pioneering Ultra-Fast Charging (UFC) Technology:** The UFC technology is poised to revolutionise the EV charging experience, offering users a refuelling process that mirrors the convenience of traditional gasoline vehicles. This is anticipated to be a game-changer in bolstering EV adoption rates for extended journeys.
- **Inherent Challenges with Contemporary Charging Stations:** The diverse array of EVs currently available in the market presents a unique set of challenges, especially when determining the optimal dimensions of the charging station and the power specifications of individual charging units.
- **Innovative Smart Charging Station Design:** The research unveils a cutting-edge smart charging station, distinguished by its modular DC/DC stage design. This ingenious configuration facilitates the even distribution of output power across varied charging ports.
- **Navigating the Optimization Conundrum:** The study adeptly models the task of designing the quintessential charging station as a singular objective optimization challenge. The primary goal here is to pinpoint the optimal number of modular shared DC/DC converters, ensuring both rapid charging and cost-effectiveness.
- **Revelatory Simulation Outcomes:** The empirical data derived from the study's simulations is illuminating. The results indicate that with a formidable installed power capacity of 800 kW, it is entirely feasible to meet the stringent demands of a UFC station equipped with 10 charging spots.
- **Envisioning the Future of Charging Stations:** The research also delves into the prospective requirements of future EVs. It underscores the imperative for forward-thinking, scalable, and modular charging stations that can seamlessly adapt to the ever-evolving needs of the EV landscape.

In the broader context of our review article, the study by Leone et al. (2021) serves as a pivotal reference point, shedding light on the intricacies of the rapidly evolving electric vehicle charging infrastructure. As we navigate the complexities of electric mobility and its

associated challenges, Leone's research offers invaluable insights into the development and optimisation of Ultra-Fast Charging Stations (UFCS). Their innovative approach to designing a modular DC/DC stage for smart charging stations underscores the importance of adaptability and efficiency in meeting the diverse needs of EV users. Furthermore, their exploration of the UFC technology, aiming to replicate the convenience of gasoline refuelling, resonates with our overarching theme of enhancing user experience and promoting wider EV adoption. By addressing both current challenges and future requirements, the study provides a comprehensive understanding that enriches our review, bridging the gap between technological advancements and practical implementation in the realm of electric vehicle charging solutions.

In the comprehensive study by Yadlapalli et al. (2022), the researchers delved deep into the intricacies of designing an optimal smart ultra-fast charging station, a topic of paramount importance in the current landscape of electric mobility [2]. As the global shift towards electric vehicles (EVs) gains momentum, the necessity for a sophisticated and efficient charging infrastructure becomes increasingly evident. The study's emphasis on ultra-fast charging (UFC) technology, which aspires to mirror the convenience of refuelling traditional gasoline vehicles, underscores its potential role as a game-changer in promoting widespread EV adoption, especially for those embarking on medium to long-distance journeys.

Yadlapalli and his team introduced an innovative smart charging station concept, leveraging a modular DC/DC stage design. This design ingeniously allows for the even distribution of output power across multiple charging ports, addressing the diverse charging needs of various EV models in the market. The research's primary objective was to meticulously determine the optimal number of these modular shared DC/DC converters, striking a balance between efficiency, charging time, and cost. Their findings were illuminating; with a power installation of 800 kW, it is feasible to cater to a UFC station equipped with 10 charging spots, showcasing the efficiency and adaptability of their proposed model.

Key Findings [9-12]:

- **Charging Infrastructure Imperative:** The surge in EV adoption underscores the pressing need for a comprehensive and efficient charging infrastructure.
- **Potential of UFC Technology:** UFC stands out as a promising solution, offering an experience reminiscent of refuelling gasoline vehicles, a crucial factor for those travelling medium to long distances.
- **Sizing Complexities:** The diverse range of EVs in the market introduces complexities in determining the optimal size of charging stations.
- **Innovative Charging Station Design:** Yadlapalli et al. championed a modular DC/DC stage design, ensuring versatile power distribution across various charging ports.
- **Optimisation Challenges:** The research astutely modelled the problem as a single-objective optimisation challenge, focusing on determining the ideal number of modular shared DC/DC converters.
- **Promising Simulation Outcomes:** The results were encouraging, indicating that an 800-kW installation could efficiently serve a UFC station with 10 charging spots.

The insights from this study are invaluable, highlighting the transformative potential of smart charging stations in the realm of electric mobility. It becomes abundantly clear that the trajectory of EV adoption is inextricably linked to the evolution and optimisation of

charging infrastructures. As the world pivots towards a more sustainable transportation model, the challenges presented by varied EV specifications and the imperative for rapid, efficient charging come to the fore. Yadlapalli et al.'s modular approach not only addresses these immediate challenges but also paves the way for future-ready solutions, ensuring that the charging infrastructure remains adaptable and relevant in the face of rapid technological advancements in EVs. This forward-thinking approach underscores the need for flexible, scalable solutions in the dynamic world of electric transportation.

In the broader context of our review article, the study by Yadlapalli et al. (2022) serves as a pivotal reference, shedding light on the pressing challenges and innovative solutions in the realm of electric vehicle charging infrastructure. Their emphasis on the optimal design of smart ultra-fast charging stations underscores a critical aspect of the EV adoption journey: the necessity for efficient, scalable, and adaptable charging solutions. As we navigate through the complexities of electric mobility, Yadlapalli's research offers invaluable insights into the modular approach to charging infrastructure, highlighting its potential to cater to the diverse needs of current EV models while ensuring adaptability for future technological advancements. Their findings resonate with the overarching theme of our review, emphasizing the symbiotic relationship between the growth of EVs and the evolution of their supporting infrastructure.

3 Future Scope of Research

The burgeoning field of electric vehicle (EV) charging infrastructure, particularly in the context of ultra-fast charging stations, presents a plethora of avenues for future research. As the adoption of EVs continues to escalate, the need for more efficient, scalable, and adaptable charging solutions becomes increasingly pressing.

- **Scalability and Modularity:** Further research could delve into how to make charging stations even more modular and scalable, adapting to a broader range of EVs and future technological advancements.
- **Grid Impact:** As ultra-fast charging stations become more prevalent, their impact on the electrical grid needs to be assessed. Future studies could focus on grid stability and demand-response strategies.
- **Renewable Energy Integration:** The integration of renewable energy sources like solar and wind power into charging stations offers an exciting area for exploration, potentially making the charging process more sustainable.
- **User Experience:** As technology advances, so do the expectations of EV users. Research into improving the user interface and experience at charging stations could be beneficial.
- **Cost-Efficiency:** While the technology exists, its high cost remains a barrier. Future research could focus on making these advanced charging stations more cost-effective.
- **Regulatory Framework:** With the technology evolving rapidly, there is a need for a comprehensive regulatory framework that can adapt to these changes.

4 Knowledge Gaps

Despite the significant strides made in the development of ultra-fast charging stations for electric vehicles, there remain several knowledge gaps that need to be addressed to propel the field forward.

- **Standardisation:** There is a lack of standardised protocols and hardware, making it challenging to create universally compatible charging solutions.
- **Long-Term Impact on Batteries:** While ultra-fast charging is convenient, the long-term impact of such rapid charging on battery health is not yet fully understood.
- **Real-World Testing:** Much of the current research is simulation-based. There is a gap in real-world testing and data collection to validate these models.
- **Energy Storage:** As renewable energy sources are more widely adopted, research into efficient energy storage solutions for off-peak charging is still in its infancy.
- **Consumer Behaviour:** There is limited understanding of how consumer behaviour affects the use and efficiency of ultra-fast charging stations.
- **Environmental Impact:** While EVs themselves are a greener alternative, the environmental impact of building and operating ultra-fast charging stations has not been thoroughly investigated.

Both these sections underscore the need for continued research and development in the realm of EV charging infrastructure. Addressing these future scopes and knowledge gaps will not only enhance the efficiency and usability of charging stations but also contribute to the broader goal of sustainable and convenient electric mobility.

The rapid evolution of electric vehicles and their associated infrastructure is a testament to the technological advancements of our age. However, as with any burgeoning field, the journey is riddled with challenges and unknowns. The integration of EVs into our daily lives is not just about the vehicles themselves but also about the entire ecosystem supporting them. This includes the charging infrastructure, the grid, renewable energy sources, and the regulatory frameworks governing them. As we stand on the cusp of a transportation revolution, it is imperative to address the existing knowledge gaps and explore potential avenues for future research. Only through a holistic approach can we ensure that the transition to electric mobility is not just efficient and sustainable, but also inclusive and accessible to all.

5 Conclusion

The transition to electric vehicles (EVs) represents a pivotal shift in the transportation sector, promising a future with reduced carbon emissions and a decreased reliance on fossil fuels. As we reflect upon the insights gleaned from the three articles under review, several key findings emerge that underscore the significance and challenges of this transition:

1. **Ultra-Fast Charging (UFC) Infrastructure:** The increasing penetration of EVs necessitates the development of robust UFC stations. These stations, as highlighted in our abstract, have the potential to offer an EV refuelling experience akin to traditional gasoline vehicles, addressing range anxiety and promoting EV adoption for longer journeys.
2. **Modularity and Scalability:** The diverse range of EVs on the market, each with its unique battery specifications, calls for charging solutions that are both modular and scalable. Such solutions can efficiently cater to varying power requirements, ensuring optimal charging times and costs.
3. **Integration of Wide Bandgap (WBG) Semiconductor Technology:** The technological advancements in the EV sector, particularly the adoption of SiC-based power semiconductor devices, have paved the way for more efficient energy

conversion, addressing challenges related to switching frequency operation, energy losses, and high-temperature performance.

4. **Energy Management Strategies (EMSs):** With EVs equipped with various energy storage elements, including lithium-ion batteries, super capacitors, and fuel cells, the importance of optimising power distribution under complex driving conditions becomes paramount. Efficient EMSs ensure optimal power flow, enhancing the overall efficiency and reliability of EVs.
5. **Challenges and Knowledge Gaps:** Despite the progress, there remain challenges related to standardisation, long-term battery health, real-world testing, and the environmental impact of charging infrastructures. Addressing these knowledge gaps is crucial for the broader adoption and success of EVs.
6. **Future Research and Development:** The reviewed articles underscore the need for continued R&D in the realm of EV charging infrastructure. From exploring renewable energy integration and user experience enhancements to understanding consumer behaviour and the environmental footprint, the journey ahead is both exciting and challenging.

In conclusion, the evolution of EVs and their supporting infrastructure is a multifaceted journey, marked by technological innovations, challenges, and immense potential. As we chart the course for a sustainable transportation future, it is essential to build upon the insights from pioneering research, such as the articles reviewed, ensuring that the transition to electric mobility is seamless, efficient, and beneficial for all.

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