Artificial Intelligence Based Control of a Superconducting Inductor Assisted DC–DC Converter for Ultra-Fast Electric Vehicle Charging

[1]Mr. P. NAGARAJU, [2]Mr. K. SIVA SANKAR, [3]S. RAMA KRISHNA, [4] R.D.A.N. SAI RAM, [5]A. NANI BABU, [6] K. SARAYU, [6] N. MANI KANTA
[12]ASSISTANT PROFESSOR, [34567]B.Tech Students,
Department of Electrical and Electronics Engineering,
D.N.R. College of Engineering and Technology, Andhra Pradesh, India

ABSTRACT

The transition toward a net-zero emission future by 2050 necessitates the large-scale adoption of battery electric vehicles (BEVs) to significantly reduce carbon emissions in the transportation sector. However, one of the primary barriers to widespread BEV deployment is the extended charging time associated with conventional systems. Faster charging demands high-power, high-voltage, and high-current operation, which often leads to efficiency losses across multiple conversion stages. Although traditional AC–DC charging systems provide relatively high efficiency, the cumulative losses from generation to battery charging typically reduce the overall efficiency to below 90%. To address these challenges, DC–DC boost converter technology emerges as a promising alternative for improving energy transfer efficiency. In this study, a superconducting DC–DC double-boost converter (SBC) is proposed and evaluated using MATLAB/Simulink. The system incorporates superconducting inductors based on Bi2223 and MgB_2 materials. Simulation results reveal that the MgB_2-based converter achieves efficiency levels above 95% for output power up to 15 kW. These findings highlight the effectiveness of superconducting technology in enabling ultra-fast, efficient, and high-performance charging solutions for next-generation electric vehicles.

Keywords: Battery Electric Vehicles, Ultra-Fast Charging, DC–DC Converter, Superconducting Inductors, MgB_2, Energy Efficiency, MATLAB Simulation

INTRODUCTION

The global transition toward sustainable energy systems has intensified efforts to reduce greenhouse gas emissions, particularly in the transportation sector, which is a major contributor to carbon dioxide (CO_2) emissions [1]. Battery electric vehicles (BEVs) have emerged as a promising solution to decarbonize transportation due to their zero tailpipe emissions and potential integration with renewable energy sources [2]. Governments and industries worldwide are actively promoting BEV adoption through policy incentives, infrastructure development, and technological advancements [3]. Despite these efforts, several technical challenges continue to hinder the large-scale deployment of BEVs, among which long charging times remain one of the most critical barriers [4]. The need for rapid and efficient charging solutions has therefore become a key focus in modern electric vehicle research. Conventional charging systems predominantly rely on AC–DC conversion stages connected to the utility grid, followed by DC–DC converters to regulate voltage and current for battery charging [5]. While these systems can achieve relatively high efficiency at individual stages, the cumulative losses across multiple conversion processes often result in an overall efficiency below 90% [6]. These inefficiencies not only increase energy consumption but also lead to additional thermal stress and reduced system reliability [7]. Furthermore, high-power fast charging requires handling elevated voltage and current levels, which impose significant design constraints on power electronic components and thermal management systems [8]. As a result, improving the efficiency and performance of charging systems is essential to support the widespread adoption of BEVs.

In recent years, DC–DC converter technologies have gained considerable attention due to their ability to provide high efficiency, flexibility, and controllability in power conversion applications [9]. Among various topologies, boost converters are widely utilized in renewable energy systems, particularly in photovoltaic applications, for maximum power point tracking and efficient energy transfer [10]. These converters can be adapted for electric vehicle charging to step up voltage levels and enable rapid energy delivery to the battery [11]. However, conventional converters still face limitations in terms of conduction losses, switching losses, and electromagnetic interference, especially under high-power operating conditions [12]. To address these limitations, the integration of superconducting materials into power electronic systems has emerged as an innovative approach. Superconductors exhibit near-zero electrical resistance when operated below their critical temperature, significantly reducing conduction losses and improving overall system efficiency [13]. Materials such as Bi2223 and magnesium diboride (MgB_2) have shown great potential for use in superconducting inductors due to their favorable electrical and thermal properties [14]. When incorporated into DC–DC converter designs, superconducting inductors can enhance energy transfer efficiency, reduce heat generation, and enable compact system architectures suitable for high-power applications [15].

In this context, the development of advanced DC–DC converter topologies incorporating superconducting components offers a promising pathway for achieving ultra-fast and efficient BEV charging. By minimizing losses and improving power handling capability, such systems can significantly reduce charging time while maintaining high efficiency. Moreover, the use of cryogenic cooling techniques, such as liquid hydrogen, further enhances the performance of superconducting devices by maintaining the required operating conditions. These advancements not only support the evolution of electric vehicle infrastructure but also contribute to the broader goal of sustainable and energy-efficient transportation systems.

LITERATURE SURVEY

The rapid advancement of battery electric vehicles (BEVs) has led to significant research efforts focused on improving charging infrastructure and power conversion technologies. One of the primary challenges identified in the literature is the limitation of conventional charging systems in delivering high power efficiently while maintaining system reliability. Early studies on AC–DC charging systems highlighted that although these systems are mature and widely deployed, they suffer from cumulative energy losses due to multiple conversion stages, resulting in reduced overall efficiency and increased thermal stress. Researchers have emphasized the need for alternative architectures that can minimize conversion losses and support high-power operation required for fast charging applications. DC–DC converter technologies have gained considerable attention as a viable solution to enhance charging efficiency. Various converter topologies, including buck, boost, buck–boost, and resonant converters, have been extensively analyzed for their suitability in electric vehicle charging systems. Among these, boost converters have been widely adopted due to their ability to step up voltage efficiently and support high-power applications. Several studies have demonstrated that interleaved and multi-phase boost converters can significantly reduce current ripple, improve dynamic response, and enhance overall efficiency. However, despite these improvements, conventional converters still experience conduction and switching losses, especially under high current conditions.

To address these limitations, researchers have explored advanced semiconductor devices such as silicon carbide (SiC) and gallium nitride (GaN) to improve switching performance and reduce losses. These wide bandgap devices enable higher switching frequencies, reduced switching losses, and improved thermal characteristics compared to traditional silicon-based components. Although these technologies enhance converter performance, they do not completely eliminate conduction losses, which remain a critical concern in high-power charging systems. This has led to increasing interest in alternative approaches that fundamentally reduce resistive losses in power electronic circuits. Superconducting technology has emerged as a promising solution in this context. Superconducting materials exhibit near-zero electrical resistance when cooled below their critical temperature, thereby drastically reducing conduction losses. Several studies have investigated the application of superconducting inductors in power converters to improve efficiency and power density. High-temperature superconductors such as Bi2223 have been widely studied due to their relatively higher critical temperatures and established fabrication techniques. More recently, magnesium diboride (MgB_2) has attracted attention because of its lower cost, simpler structure, and favorable superconducting properties.

Comparative analyses have indicated that MgB_2 offers improved performance in terms of current carrying capability and efficiency under practical operating conditions.

In addition to material advancements, research has also focused on the design of novel converter topologies incorporating superconducting elements. Double-boost and multi-stage converter configurations have been proposed to achieve higher voltage gain and improved power transfer efficiency. Simulation-based studies using platforms such as MATLAB/Simulink have demonstrated that superconducting DC–DC converters can achieve efficiency levels exceeding those of conventional converters, particularly in high-power applications. These systems also exhibit reduced thermal losses, enabling more compact and reliable designs. Furthermore, the integration of cryogenic cooling systems has been investigated to maintain the operating conditions required for superconductivity. Liquid hydrogen and liquid nitrogen cooling methods have been explored for their effectiveness in sustaining low temperatures while ensuring system stability. Although the incorporation of cooling systems introduces additional complexity, studies have shown that the overall efficiency gains and performance improvements justify their implementation in high-power charging applications.

Overall, the literature indicates a clear trend toward the development of high-efficiency, high-power DC–DC converter systems for ultra-fast electric vehicle charging. While conventional and wide bandgap semiconductor-based converters offer incremental improvements, superconducting technologies provide a transformative approach by significantly reducing conduction losses. The combination of advanced materials, innovative converter topologies, and effective cooling techniques presents a promising pathway for next-generation charging systems capable of meeting the growing demands of electric mobility.

METHODOLOGY

The methodology begins with defining the system requirements for ultra-fast charging of battery electric vehicles, focusing on achieving high efficiency, high voltage gain, and stable operation under high current conditions. The target specifications include an output power level of up to 15 kW, efficiency exceeding 95%, and the ability to operate under varying load and input conditions. Based on these requirements, a DC–DC double-boost converter topology is selected due to its capability to provide high voltage gain and improved energy transfer characteristics compared to conventional single-stage converters.

The next step involves the design of the converter topology. The double-boost configuration is structured using two cascaded boost stages, each consisting of an inductor, switching device, diode, and output capacitor. The key innovation in this methodology is the replacement of conventional inductors with superconducting inductors to minimize conduction losses. Two types of superconducting materials, namely Bi2223 and MgB_2, are chosen for analysis due to their established performance characteristics and suitability for power applications. The inductors are modeled considering their near-zero resistance property under cryogenic conditions, while also incorporating practical parameters such as critical current limits and magnetic field constraints.

Following the topology design, mathematical modeling of the converter is carried out to establish the relationship between input voltage, duty cycle, and output voltage. The governing equations for each boost stage are derived based on the principles of inductor volt-second balance and capacitor charge balance. These equations are then combined to represent the overall behavior of the double-boost converter. Special attention is given to ensuring continuous conduction mode (CCM) operation, which is essential for reducing current ripple and improving efficiency. The duty cycle is optimized to achieve the desired output voltage while maintaining system stability.

The methodology then proceeds with the development of a simulation model using MATLAB/Simulink. The converter circuit is implemented using standard power electronic components, and the superconducting inductors are represented using customized blocks that reflect their low-resistance characteristics. Switching devices are modeled with appropriate parameters to capture realistic switching behavior, including switching losses and conduction losses.

Pulse width modulation (PWM) techniques are employed to control the switching of the converter, and a suitable switching frequency is selected to balance efficiency and dynamic performance.

In the next step, a control strategy is implemented to regulate the output voltage and ensure stable operation under varying load conditions. A closed-loop control system is designed using a proportional-integral (PI) controller, which continuously monitors the output voltage and adjusts the duty cycle of the switches accordingly. The controller parameters are tuned to achieve fast dynamic response, minimal overshoot, and steady-state accuracy. The performance of the control system is validated under different operating scenarios, including load variations and input voltage fluctuations.

The simulation study is then conducted to evaluate the performance of the proposed system. Two separate cases are analyzed, one using Bi2223 inductors and the other using MgB_2 inductors. Key performance metrics such as efficiency, output voltage regulation, current ripple, and power loss are measured and compared. The results are analyzed to determine the effectiveness of superconducting inductors in improving system performance. Particular emphasis is placed on efficiency improvement and reduction in thermal losses, which are critical for high-power charging applications.

Finally, the methodology includes a comparative analysis of the results obtained from both superconducting materials. The performance of the MgB_2-based converter is evaluated against the Bi2223-based system to identify the more suitable material for practical implementation. The findings are interpreted to assess the feasibility of integrating superconducting technology into real-world electric vehicle charging infrastructure. This step-by-step approach ensures a comprehensive evaluation of the proposed converter system, from design and modeling to simulation and performance analysis, providing valuable insights into its potential for ultra-fast and efficient BEV charging applications.

PROPOSED SYSTEM

The proposed system presents an advanced superconducting DC–DC double-boost converter designed to enable ultra-fast and highly efficient charging for battery electric vehicles. The architecture is developed to overcome the limitations of conventional charging systems by minimizing conduction losses and enhancing power transfer capability under high-voltage and high-current operating conditions. The system primarily consists of two cascaded boost converter stages, superconducting inductors, high-speed switching devices, diodes, output capacitors, a control unit, and a cryogenic cooling mechanism to maintain superconducting conditions. At the core of the system is the double-boost converter topology, which is selected for its ability to achieve a higher voltage gain compared to single-stage converters. The first boost stage receives the input DC supply and elevates the voltage to an intermediate level, while the second stage further increases the voltage to the required level suitable for rapid battery charging. This cascaded configuration ensures efficient energy transfer while maintaining stability and reduced stress on individual components. The switching operation in both stages is controlled through pulse width modulation, allowing precise regulation of the duty cycle to achieve the desired output voltage.

A key innovation in the proposed system is the integration of superconducting inductors in place of conventional copper-based inductors. These inductors are implemented using high-temperature superconducting materials such as Bi2223 and magnesium diboride. When cooled below their critical temperature, these materials exhibit near-zero electrical resistance, which significantly reduces conduction losses and improves overall system efficiency. Among the two materials, MgB_2 is particularly advantageous due to its lower cost, higher current carrying capacity, and better thermal stability, making it a suitable candidate for high-power applications. To maintain the superconducting state, a cryogenic cooling system is incorporated into the design. Liquid hydrogen is considered as the cooling medium due to its extremely low temperature and high cooling efficiency. The cooling system ensures that the superconducting inductors operate within their critical temperature range, thereby sustaining their zero-resistance property. Proper thermal insulation and safety measures are included to manage the cryogenic environment and ensure reliable operation.

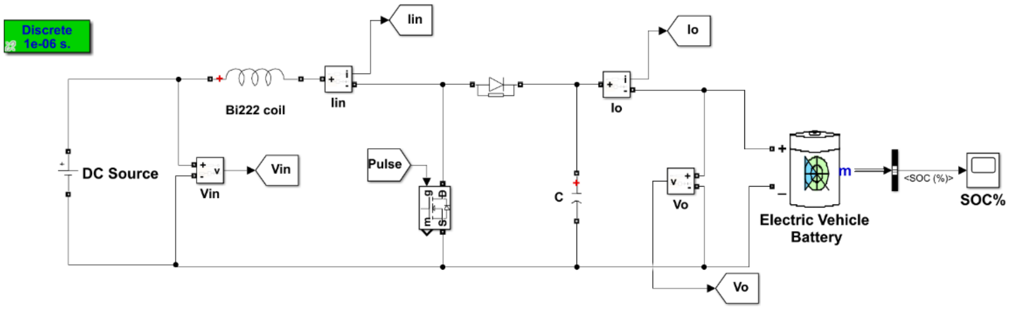


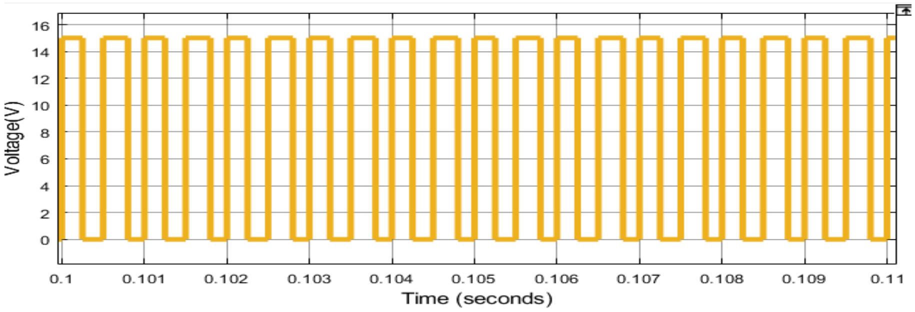
Fig 1: Circuit topology of Bi2223 converter

The system also includes a closed-loop control mechanism to regulate the output voltage and maintain stable charging conditions. A proportional-integral controller continuously monitors the output voltage and compares it with a reference value corresponding to the battery charging requirement. Based on the error signal, the controller adjusts the duty cycle of the switching devices in both boost stages. This dynamic control approach ensures fast response, minimal voltage fluctuations, and consistent performance under varying load and input conditions. In addition to voltage regulation, the proposed system is designed to operate in continuous conduction mode to reduce current ripple and improve efficiency. The use of superconducting inductors further contributes to smoother current flow and reduced electromagnetic interference. The system is capable of delivering high output power, up to 15 kW, while maintaining efficiency levels exceeding 95%, making it highly suitable for ultra-fast charging applications.

Overall, the proposed system offers a significant advancement in electric vehicle charging technology by combining high-efficiency DC–DC conversion with superconducting components and cryogenic cooling. This integrated approach not only reduces energy losses but also enhances power density and system reliability. The design demonstrates strong potential for next-generation charging infrastructure, supporting faster charging times and improved energy utilization, thereby contributing to the widespread adoption of electric vehicles.

RESULTS AND DISCUSSION

The performance of the proposed superconducting DC–DC double-boost converter was evaluated through detailed simulations conducted in MATLAB/Simulink under varying operating conditions. The primary objective was to assess the effectiveness of superconducting inductors in enhancing efficiency, reducing losses, and supporting high-power ultra-fast charging requirements. The system was tested for output power levels up to 15 kW, with both Bi2223 and MgB_2 superconducting materials incorporated separately in the inductor design. Key performance parameters such as output voltage regulation, efficiency, current ripple, and power losses were analysed to determine the feasibility of the proposed configuration.



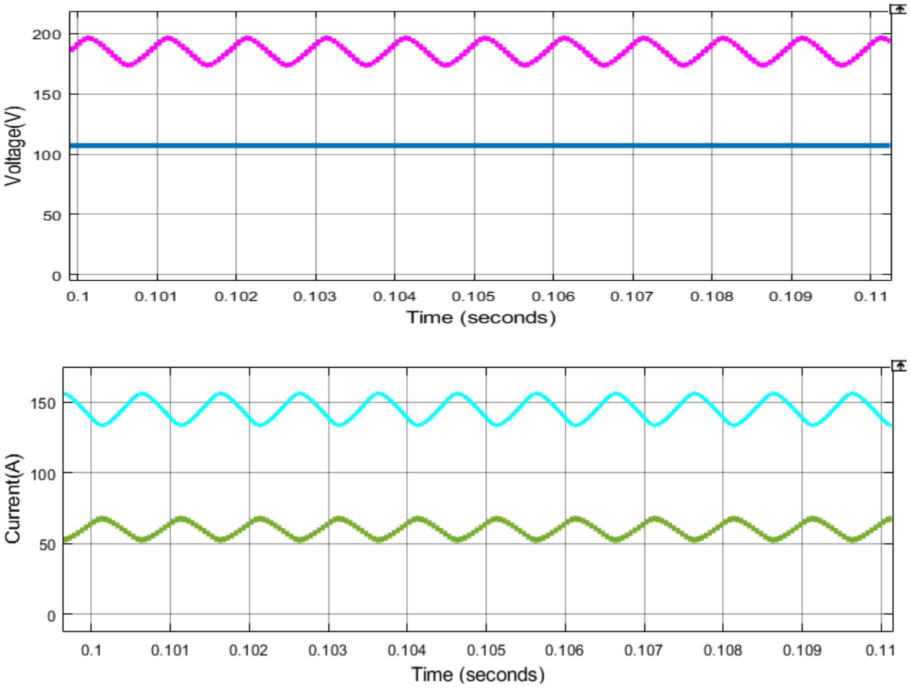


Fig 2: Typical waveforms of MgB2 converter

The simulation results demonstrate that the proposed converter is capable of achieving stable and high voltage output suitable for fast charging applications. The double-boost topology effectively increases the input voltage to the desired level while maintaining consistent performance across varying load conditions. The output voltage was observed to remain well-regulated with minimal fluctuations, even during transient changes in load demand. The implementation of a closed-loop control strategy ensured rapid response and accurate tracking of the reference voltage, thereby enhancing the reliability of the charging system. The system also successfully operated in continuous conduction mode, contributing to smoother current flow and reduced ripple.

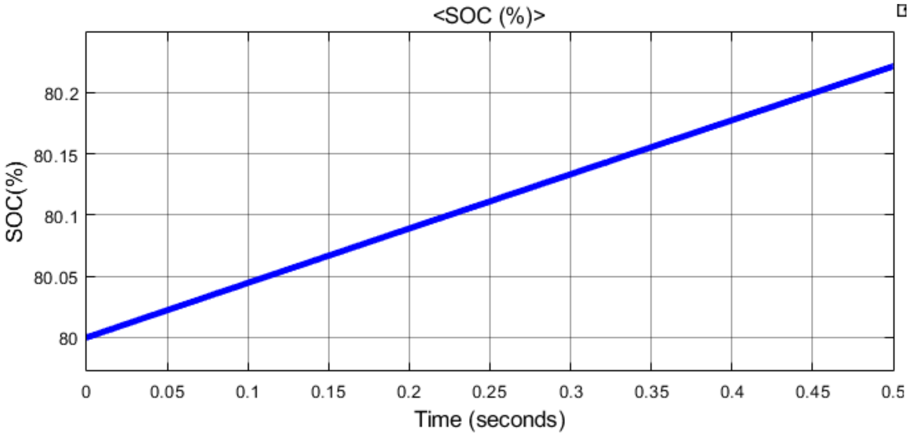


Fig 3: SOC% of the EV battery

A significant improvement was observed in system efficiency when superconducting inductors were employed. The converter using MgB_2 inductors achieved efficiency levels exceeding 95% across a wide range of operating conditions, particularly at higher power levels. In comparison, the Bi2223-based system also showed improved efficiency over conventional designs but exhibited slightly lower performance than MgB_2 due to its relatively higher losses and material limitations. The near-zero resistance characteristic of superconducting inductors played a crucial role in minimizing conduction losses, which are typically dominant in high-current applications. This reduction in losses directly contributed to improved energy transfer efficiency and reduced heat generation within the system.

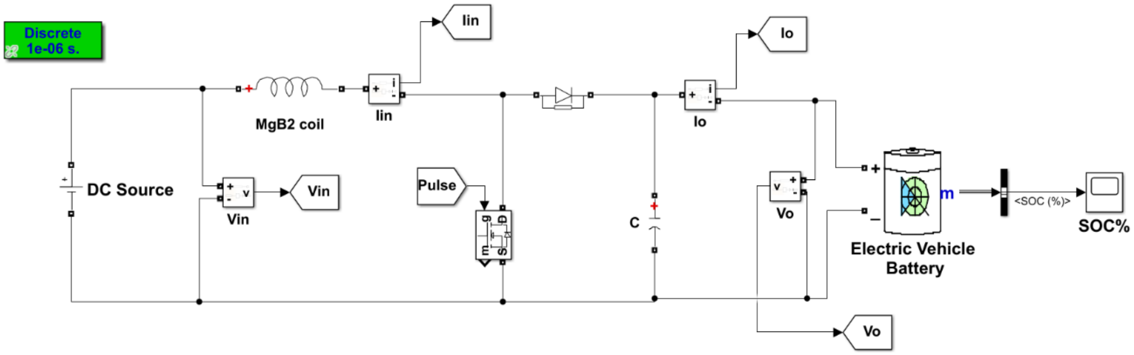
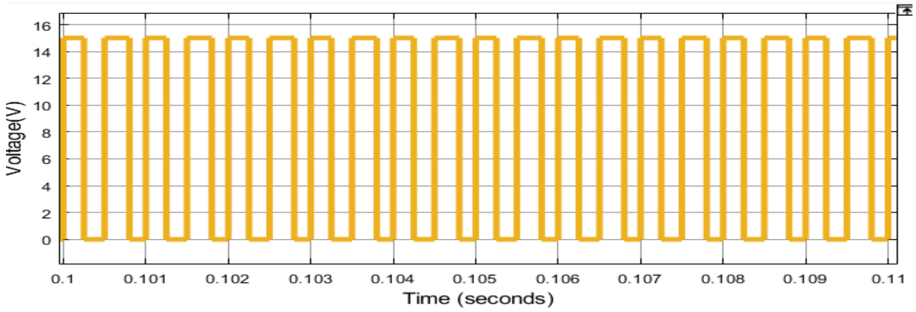
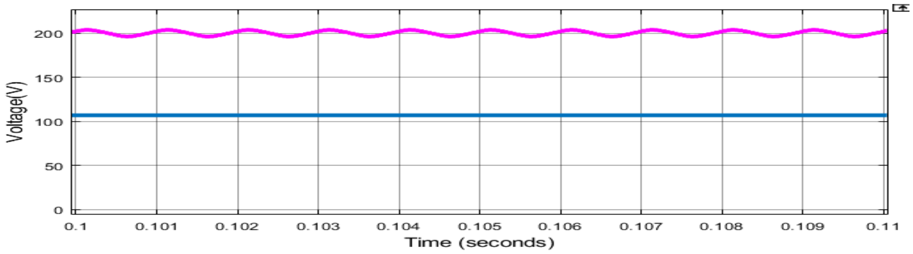


Fig 4: Circuit topology of MgB2 converter

The analysis of power losses further highlights the advantages of the proposed system. Conventional DC–DC converters typically experience significant conduction and switching losses, especially under high-power operation. In contrast, the superconducting converter exhibited a substantial reduction in conduction losses due to the elimination of resistive elements in the inductors. Although switching losses were still present due to semiconductor devices, their impact on overall efficiency was comparatively lower. Additionally, the reduced thermal stress on components enhances system reliability and potentially extends the lifespan of the converter. The lower heat dissipation requirements also simplify thermal management compared to traditional systems.





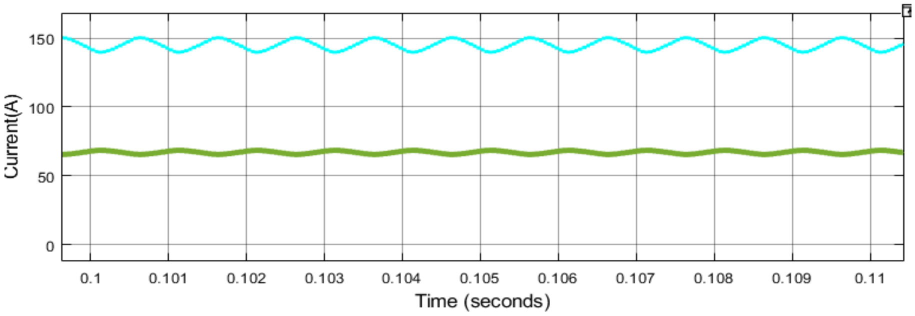


Fig 5: Typical waveforms of MgB2 converter

Current ripple and electromagnetic performance were also evaluated as part of the study. The results indicate that the use of superconducting inductors, combined with the double-boost topology, effectively reduces current ripple in both stages of the converter. Lower ripple levels contribute to improved battery charging characteristics, as excessive ripple can negatively impact battery life and performance. Furthermore, reduced electromagnetic interference enhances system stability and compatibility with other electronic components. The continuous conduction mode operation ensured that the current remained stable throughout the switching cycle, further supporting efficient and reliable performance.

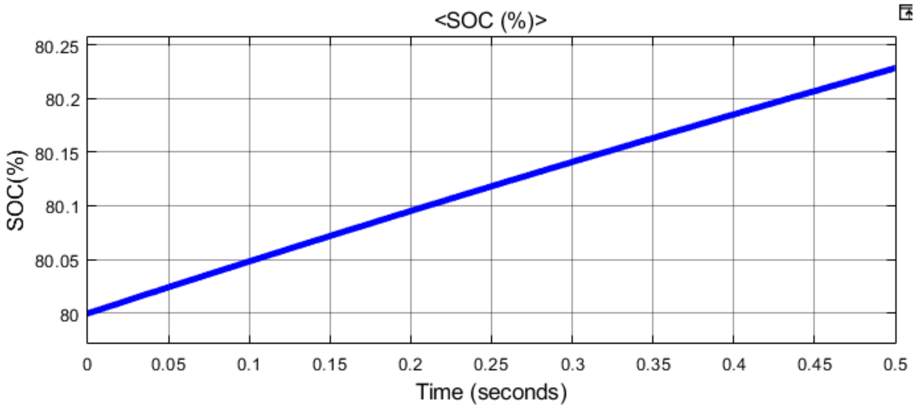


Fig 6: SOC% of the EV battery

Overall, the results confirm that the proposed superconducting DC–DC double-boost converter offers significant advantages over conventional charging systems. The integration of MgB_2 superconducting inductors, in particular, provides superior efficiency, reduced losses, and enhanced performance under high-power conditions. The system demonstrates strong potential for ultra-fast electric vehicle charging applications, achieving high efficiency while maintaining stable operation and improved power quality. These findings validate the effectiveness of combining advanced converter topologies with superconducting technology, paving the way for next-generation energy-efficient charging infrastructure.

CONCLUSION

The study presented an advanced superconducting DC–DC double-boost converter designed to enable ultra-fast and efficient charging for battery electric vehicles. By integrating superconducting inductors into the converter topology, the proposed system effectively minimizes conduction losses and enhances overall energy transfer efficiency. The use of Bi2223 and MgB_2 materials demonstrated the practical feasibility of incorporating superconducting technology into high-power charging applications. Among these, the MgB_2-based system exhibited superior performance, achieving efficiency levels exceeding 95% while maintaining stable operation under high-voltage and high-current conditions.

The simulation results confirmed that the proposed converter provides excellent voltage regulation, reduced current ripple, and improved thermal performance compared to conventional systems. The implementation of a closed-loop control strategy further ensured reliable and dynamic response under varying load conditions. Although the inclusion of cryogenic cooling introduces additional complexity, the significant gains in efficiency and performance justify its application in next-generation charging infrastructure. Overall, the proposed system represents a promising solution for addressing the challenges of prolonged charging times in electric vehicles. It contributes to the development of high-performance, energy-efficient charging technologies, supporting the broader goal of sustainable and rapid electrification of transportation systems.

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