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High-Efficiency Bidirectional DC-DC Converter with Interphase Transformer for Electric and Aerospace Applications

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Abstract: The importance of power density and converter efficiency is growing in the electric car industry. Losing weight is one way to lower the power consumption of an electric car. An efficient DC-DC bidirectional converter (12V to 48V) with a power density of 1.5 kW is demonstrated in this dissertation report. This converter made use of planar magnetics, a substrate with thermal conductivity, and cooling semiconductors with two sides. The design of the converter was a double interleaved boost based on an interphase transformer. To guarantee that power could flow in both directions, the circuit's design included a full bridge. Magnetic cores, capacitors, heat sinks, and connections were all part of the semiconductor devices that were optimized for electrical, mechanical, and thermal aspects. The use of a thermal clad board allowed for the symmetry of the power circuit and the reduction of parasitic impedance. The efficiency of the dual interleaved boost converter was tested in both static and dynamic modes of operation. Theory and criteria were satisfied by all waveforms. Coil current sharing and strong coupling are features of the planar interphase transformer. Design predictions for temperature and power loss were met by a number of components. The efficiency of both the boost and buck modes was 94% under the rated condition. With and without heat sinks, the power densities were 1.8 kW/liter and 5.1 kW/liter, respectively. An example of how commercially available components can achieve high efficiency and power density is demonstrated by the proposed converter. This converter allows an electric vehicle to attach additional loads to its 12V battery. Aircraft and electric ships both use it for the same purpose.

Keywords: DC-DC Bidirectional Converter; High Efficiency; Power Density; Electric Vehicles; Planar Magnetics; Interphase Transformer; Boost Architecture; Thermal Optimization.

Introduction

In the current automotive landscape, power electronic converters play a critical role in enabling the efficient operation of electric vehicles (EVs) [7]. These converters serve as essential interfaces between the vehicle's power sources—such as batteries, fuel cells, and supercapacitors—and its electrical loads, including motors, actuators, and a wide range of electronic accessories [8]. A major challenge in advancing EV technology lies in reducing the size and cost of these converters while simultaneously improving their efficiency [9]. Achieving these goals could significantly enhance the mass-to-performance ratio of EV systems, thereby reducing overall vehicle weight [10]. This reduction leads to decreased energy and fuel consumption, which is paramount for promoting sustainability across transportation modes like electric vehicles, aircraft, and ships [11].

By increasing power density, which refers to the amount of power processed per unit volume or mass, modern converters outperform their traditional counterparts [12]. However, this also introduces greater thermal, electrical, and mechanical stress, making it increasingly complex to balance performance with reliability [13]. Thus, developing highly power-dense converters with excellent efficiency remains one of the foremost challenges in realizing greener transportation systems [14].

The automotive industry has made remarkable strides over the past two decades in introducing diverse types of EVs into the market. Among these, three categories have gained widespread acceptance: plug-in hybrid electric vehicles (PHEVs), fuel cell electric vehicles (FCEVs), and hybrid electric vehicles (HEVs) [15]. Despite the superior environmental credentials of fully electric vehicles (EVs), their mass adoption faces several barriers [16]. These include higher production costs, prolonged battery charging times, limited operational range, and a heavy reliance on power grids [17]. Consequently, these factors have contributed to the comparatively slower acceptance of pure EVs, even though they are more efficient and environmentally friendly [18]. Hybrid electric vehicles combine internal combustion engines with electric motors, powered by rechargeable batteries [19]. These batteries are essential for the functioning of HEVs, which have evolved through different stages—from micro-hybrid systems to mild hybrid setups and eventually to full hybrid vehicles [20]. Full HEVs, like the Volkswagen Touareg TSI Hybrid, Mercedes M-Class Hybrid, Lexus RX 400h, BMW X6, and Toyota Prius, are capable of running solely on electric power and are equipped to handle all electric-based functionalities within the vehicle, including traction and auxiliary systems [21].

Fuel cell electric vehicles take the innovation further by replacing the traditional combustion engine with a hydrogen fuel cell [22]. This enables zero-emission performance. However, despite their promising environmental benefits, fuel cell vehicles are still not commercially widespread due to technological challenges such as the complexity of hydrogen storage, the need for advanced reformers, and issues related to water byproduct management [23]. These challenges contribute to the high cost and limited deployment of fuel cell systems [24]. Moreover, they typically require supplemental energy storage components like batteries or supercapacitors due to their limited voltage regulation capabilities [25]. Plug-in hybrid electric vehicles, on the other hand, enjoy an edge over conventional HEVs by offering the capability to recharge from standard electrical outlets [26]. This additional flexibility enhances their usability, particularly in urban environments where daily travel distances are often within the electric-only range offered by PHEVs [27]. Notable examples include the Mercedes Vision S500 Plug-in Hybrid, Chevrolet Volt, and the Toyota Prius Plug-in Hybrid [28]. These vehicles are often seen as the most practical option in today's EV market, offering a favorable balance between energy efficiency and usability [29].

A significant limitation in the current EV landscape is the absence of a universal electrical architecture within the vehicle. Different EV configurations use various methods to power the main traction motor [30]. The three primary configurations are series, parallel, and series-parallel. In the series configuration, both the engine and battery are aligned in series to supply energy [31]. In the parallel configuration, the battery and engine operate in tandem to deliver power, whereas the series-parallel setup combines features of both [32]. Across these configurations, a high-power DC-DC converter is a crucial component that ensures voltage transformation from 200–300 volts at the battery end to approximately 500–700 volts at the inverter end of the motor drive [33]. Additionally, components like flywheels or supercapacitors are often employed to act as peak power buffers [34]. These elements interface with the high-voltage DC link through smaller-scale DC-DC converters, playing a pivotal role in power management during transient load conditions [35]. Apart from traction systems, electric vehicles incorporate numerous auxiliary loads such as electric power steering, air conditioning units, infotainment systems, lighting, and safety mechanisms [36]. These systems typically operate at lower voltages—around 12V or 42V—and require separate power management strategies [37]. For this purpose, low-power DC-DC converters are used to link these auxiliary systems to the main powertrain [38]. For instance, several hybrid vehicle models, including the Toyota Lexus, GMC Yukon by General Motors, and

Chevrolet Tahoe, employ converters that modify the main battery's voltage from 300V to 42V, making it suitable for powering components like electronic steering systems [39]. In addition to these powertrain components, some hybrid systems integrate starting alternator technologies. In such configurations, a starter alternator powered by a belt is used in tandem with the main engine to support auxiliary power unit (APU) functionality [40]. In some advanced systems, fuel cells or battery-powered APUs are explored to achieve more efficient power generation at higher voltages like 42V [41].

Given the expanding electrical demands within EVs, the adoption of dual-voltage architecture, particularly 42V/12V systems, has emerged as a practical solution [42]. This dual-bus system ensures more efficient and flexible power delivery across both high and low power demands [43]. Consequently, one of the emerging research areas involves determining the most stable and efficient way to manage power between these two voltage buses. Two options are currently under consideration [44]. The first involves standardizing the entire system at a lower voltage like 12V or 14V while using separate, dedicated DC-DC converters to manage higher power loads (at 42V or 48V) [45]. The second approach is to develop an advanced bidirectional DC-DC converter that can manage power flow in both directions, offering enhanced energy efficiency and control [46]. To address this need, a project was undertaken to develop a highly power-dense and efficient bidirectional DC-DC converter that converts 12V to 48V and vice versa [47]. This converter leverages cutting-edge technologies, including double-sided cooling semiconductor switches, high-power planar magnetic components, and thermally conductive substrates to achieve high performance in a compact footprint [48]. Surface-mount components were chosen throughout the design to minimize space requirements and optimize thermal management [49]. All design choices, including component selection and circuit topology, were guided by a holistic optimization strategy targeting electrical, mechanical, and thermal performance [50].

The experimental results of the developed converter demonstrated impressive performance metrics. At a rated power of 1.5 kilowatts, the converter achieved an efficiency level of approximately 94% [51]. This figure reflects the system's ability to minimize power loss during conversion, making it suitable for use in modern electric vehicles where energy efficiency is paramount [52]. While the project specifically focused on 12V to 48V conversion, the same system architecture can easily be adapted to other voltage levels, such as 12V to 42V or 14V to 42V, by simply modifying the duty cycles of the semiconductor switches [53]. This adaptability further enhances the converter's applicability across different EV platforms, allowing for flexible integration into a variety of auxiliary power systems. The successful development of this converter marks a significant step forward in meeting the evolving power demands of electric vehicles [54]. As the transportation sector continues to shift toward electrification, innovations in power electronics—such as this bidirectional DC-DC converter—will play a vital role in overcoming existing limitations related to efficiency, weight, and cost [55]. By enabling compact, efficient, and robust power conversion, such technologies pave the way for the next generation of electric transportation solutions, contributing meaningfully to the global sustainability agenda.

Literature Review

A small-signal, sampled-data model is developed for a dual-interleaved boost converter that includes the interphase transformer's differential inductance and a peak current-mode controller. This model leverages half-cycle waveform symmetry and is validated using Saber simulation and a 10-kW prototype. The study reveals significant dynamic differences based on the duty ratio: for $D \leq 0.5$, slope compensation is necessary to avoid subharmonic instability, especially when the inductance ratio exceeds 4.0. The control-to-output transfer function also becomes sensitive to inductance changes in this mode. In contrast, for $D > 0.5$, the need for slope compensation decreases as the inductance ratio increases. These findings underscore the importance of duty ratio and inductance values in designing stable and efficient power converters for electric vehicle applications [1].

The automotive industry is undergoing a transition toward more electrical systems to meet rising vehicular load demands. Over the next 10 to 20 years, automotive power systems must evolve significantly to support this shift. Presently, rising fuel economy standards and the demand for more onboard electric power are pushing system voltages higher. Forecasts suggest that future vehicles could require power levels as high as 10 kW—three to four times today's demand. Meeting this challenge necessitates integrating power electronics-based solutions within vehicle systems. This paper aims to review the current and future landscape of electrical power systems in electric, hybrid electric, and fuel cell vehicles, with a particular focus on the architectures and applications of DC/DC and DC/AC converters [2].

This study explores power interface options for PEM fuel cells, focusing on part-load operation and its impact on component selection and magnetic stress. A comparison is made between a standard two-phase interleaved boost converter and a transformer-coupled version that includes a single input inductor and a phase-coupling transformer. Using experimental voltage-current input profiles derived from an industrial PEM fuel cell's polarization curve, the research evaluates the performance of a 3 kW prototype. It also includes an investigation into the magnetic design and sizing of air-cooled components for higher power ranges up to 45 kW. This analysis helps optimize the use of magnetic components and supports the efficient design of fuel cell converter systems in electric vehicles [3].

This paper discusses the design and construction of a high-power bidirectional DC-DC converter used to link a supercapacitor energy buffer with a higher voltage traction system in compact electric vehicles. The proposed 18 kW dual interleaved boost converter features an interphase transformer and is carefully designed to maximize both volumetric and gravimetric power density. The physical layout simplifies assembly and enhances thermal management. The resulting prototype achieves impressive power densities of 6.5 kW/kg and 7.9 kW/l. Efficiency results and thermal performance are presented alongside a detailed mass and loss audit of key components. This converter addresses the challenge of compact, lightweight power solutions for high-efficiency energy transfer in modern EVs [4].

Improving the efficiency of full-bridge DC-DC converters in plug-in hybrid electric vehicles (PHEVs) is essential for extending driving range and reducing energy loss. This paper presents a new technique that enhances zero-voltage switching (ZVS) in converters connecting the high-voltage traction battery to the 12V battery. A passive asymmetrical auxiliary circuit is used to expand the soft-switching range but creates extra circulating currents. The proposed method minimizes these currents by adjusting the switch duty cycle, reducing conduction losses and improving efficiency, particularly at light loads. A 2 kW converter is tested, showing significant gains in efficiency. This approach provides a practical solution to enhance energy conservation in PHEV powertrains [5].

This paper outlines key modeling strategies for simulating power electronic devices, whether operating independently or integrated into broader power systems. It covers various methods for representing power converters and semiconductor devices accurately. A brief overview of the Alternative Transients Program (ATP) is included, highlighting its usefulness in simulating power electronic circuits. The paper details how ATP's capabilities can model components typically found in power electronics systems. It also provides general modeling guidelines and discusses simulation challenges. Finally, the paper presents case studies showcasing power electronics applications in transmission, distribution, and renewable energy systems, demonstrating how simulation supports system design and optimization [6].

Methodology

This paper presents the methodology for designing a 1.5 kW bidirectional DC-DC boost converter, specifically aimed at achieving a voltage conversion ratio of four, from 12V to 48V. The design process began with selecting a suitable converter topology based on a comparative analysis of switch losses. Among the various options, the dual interleaved boost converter topology, integrated with an interphase transformer, was identified as the most optimal configuration for the desired power rating and voltage gain. The choice of this topology is justified by its inherent advantages in terms of improved efficiency, reduced ripple current, and superior thermal performance due to current sharing across phases [56].

Following the topology selection, the steady-state operation of the circuit was thoroughly analyzed to establish essential design parameters [57]. Analytical equations were developed to facilitate component sizing, ensuring the converter's performance remains robust under the intended operating conditions. The main objective of this phase was to derive relationships for inductor current, switch duty cycle, voltage gain, and current ripple, which are fundamental to the converter's efficient functioning [58]. The circuit components were then carefully selected based on these design equations to ensure a balanced trade-off between electrical, thermal, and mechanical performance [59]. Critical components, such as inductors, capacitors, and switching devices, were chosen with attention to minimizing losses, achieving compactness, and ensuring thermal stability [60].

Two fundamental circuit configurations were considered in this analysis—unidirectional and bidirectional boost converters [61]. The basic structure of a conventional unidirectional boost converter includes an inductor, a switching device, and a capacitor [62]. In contrast, the bidirectional version employs two active switches configured to enable power flow in both directions [63]. In the bidirectional configuration, switching polarity is reversed as required, utilizing the body diode of one switch and the conduction of the other to facilitate reverse power flow [64]. This feature is particularly important for applications involving energy regeneration or battery charge-discharge cycles.

Result and Discussion

The designed converter operates in two primary modes: continuous inductor current mode (CCM) and discontinuous inductor current mode (DCM). In either mode, the inductor stores energy when a switch is in the on-state and transfers it to the load when the switch is turned off. However, the selection of operating mode significantly impacts the design of passive and active components [65]. DCM operation, while beneficial for enabling zero voltage switching (ZVS), also introduces challenges such as increased electromagnetic interference (EMI) and higher conduction losses in the switches due to current discontinuity [66]. Despite these drawbacks, ZVS in DCM allows for high-frequency operation with minimal switching loss, making it advantageous for power-dense converter applications. Thus, careful consideration was given to balancing the benefits of high-frequency operation with the need to manage EMI and thermal stress [67]. The outcome is a highly efficient, compact, and thermally optimized converter suitable for use in modern electric vehicle architectures and other high-performance power conversion applications [68].

The use of these designs in more modern electric vehicle models was illustrated in reference [69]. A typical powertrain design for series, parallel, and series-parallel hybrid electric vehicles is depicted in the figure 1 [70]. In the series configuration, the engine and battery are connected in series through an alternator and rectifier [71].

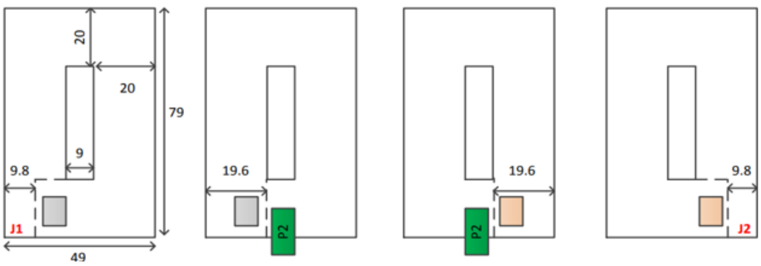

Figure 1: Four individual IPT turns, dimensions, and interconnecting points(mm)

Figure 2 depicts the top view of the converter following the connection of the inductor and IPT to the T-Clad board. In reality, cables were used to measure the currents flowing through them even though they were used to connect the T-Clad board and the IPT [72]. IPT will be mounted above the input connector in the finished product, and planar copper bus bars will be used to connect it to J1 and J2 [73]. A bank of variable resistors was set up that could provide a load value between 1.5 and 18.5 Ω. In light of the 12 V to 48 V operation, the converter may be tested for a power range of 124.5 W to 1500 W [74]. A gate drive circuit from the lab was utilized to operate the converter in open loop mode. Two IPT windings have two current probes linked to them. During the experiments, multimeters and necessary voltage probes were also connected [75]. The temperature of the components was tracked using an infrared imaging camera (Figure 2).

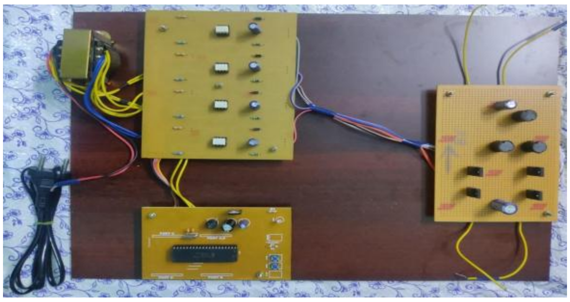

Figure 2: Top view of the converter circuit

Recent advancements in materials, components, and circuit topologies have significantly accelerated progress in power electronics, leading to more compact, efficient, and power-dense converter designs [76]. These improvements are particularly relevant to the electric vehicle (EV) industry, which increasingly relies on advanced power electronic solutions to enhance vehicle performance and compete with traditional fuel-powered counterparts [77]. Research in this area has become increasingly critical, with power electronics potentially contributing up to one-third of an EV's total cost [78]. This study demonstrated the feasibility of developing a high-efficiency, high-density 12V to 48V bidirectional DC-DC converter rated at 1.5 kW. This converter can be a valuable component of an EV’s auxiliary power unit, enabling the connection of auxiliary loads to either the drivetrain or a 12V battery system [79]. Beyond EVs, similar converter configurations are also applicable in electric ships and aircraft. The research presented in this paper covers an overview of the entire design process, key contributions, design trade-offs, and areas for future work [80].

To begin, a thorough literature review was conducted, examining electric vehicle powertrain architectures, topological comparisons, magnetic material innovations, and semiconductor technologies [81]. The goal was to identify a converter design with minimal components while maintaining high performance [82]. Among the various topologies evaluated, the dual interleaved boost converter with an interphase transformer was selected for its efficiency and power density advantages. Design equations were developed based on an operational analysis of the circuit [83]. The DirectFet International Rectifier MOSFET was chosen for its low profile, superior cooling capacity, and robust performance [84]. A thermal-clad substrate was selected to complement the power device's thermal performance [85]. Thermal modeling was performed for the MOSFET to ensure effective heat management and to refine the thermal layout of the converter.

The converter design involved two core magnetic components, each chosen for specific functional roles. The input inductor, which supports the full power load, required a core material with high saturation flux density, leading to the selection of an amorphous-metal core. In contrast, the interphase transformer handled only ripple currents and therefore used a low-loss ferrite core with lower saturation flux. To minimize weight and volume, a planar transformer configuration was employed for the IPT. Both magnetic components were designed using optimized core and winding configurations based on current density, window area utilization, and minimal ripple criteria. High-performance multilayer ceramic capacitors were used for input and output filtering due to their compact size and strong thermal capability [86].

The final assembly was built on a thermal-clad, single-sided board with a symmetrical power circuit layout to reduce parasitic effects. A heat sink was selected following a detailed power loss audit. Special attention was paid during construction to ensure precision in inductance values and effective winding coupling in the IPT, achieved through a custom fabrication method. Testing validated the converter's excellent performance in both buck and boost modes, exhibiting accurate current sharing and minimal ripple in accordance with the design. Thermal tests confirmed that the converter could operate reliably at full load for extended periods. The resulting design achieved a power density of 1.8 kW/liter and an efficiency of approximately 94%, confirming its effectiveness and suitability for integration in modern EV power systems.

Conclusion

A DC-DC boost converter is becoming increasingly essential in the development of advanced electric vehicle (EV) systems. Ongoing research in both academic and industrial sectors focuses on improving these converters, with power density being the most critical design factor. A higher power density ensures compact, efficient, and cost-effective solutions suitable for the competitive automotive market. The 12V to 48V bidirectional DC-DC converter plays a vital role in linking auxiliary systems, such as connecting 48V loads to a 12V battery or interfacing the 12V and 48V power buses within an EV. To meet these needs, a power-dense converter using an interphase transformer (IPT)-based dual interleaved boost topology was selected for its high efficiency and proven compactness. This topology is favored for its small magnetic circuit design and reduced ripple currents, especially at higher frequencies. Efforts are now being made to enhance the current architecture for further miniaturization. Early project work includes a detailed study of the circuit and magnetics. Research has identified that the input inductor and IPT design are crucial to achieving high power density. A planar magnetic design is being explored for the IPT, while amorphous metal cores are considered for the input inductor despite design challenges due to limited core shapes.

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