A Comprehensive Investigation into Bidirectional DC-DC Converters with Soft Switching for Electric Vehicles

Abstract: Electric vehicles (EVs) are one of the promising solutions for the environmental issues such as carbon emission and global warming. The high voltage traction battery in EVs is charged from utility grid by an EV charger. The Society of Automotive Engineers (SAE) standardize EV charges into two categories on-board chargers and off-board chargers. Usually, the on-board chargers are located inside the vehicle whereas, off-board chargers are not mounted on the vehicle. For onboard chargers, size and power density of charger become a prior matter of concern. The only way to reduce the size of a converter and thereby increase the power density is to operate power electronic conversion system (PECS) at very high switching frequency (HSF) resulting in reduced size of magnetic component in the charger configuration. However, HSF operation may lead to a high electromagnetic interference (EMI), loss in switch and switch duty. The work in this paper is focused on the development of high frequency bi-directional DC-DC converter (BD2C) stage priority used in on-board chargers due to distributed sources of energy as well as to manage the power distribution in the configuration. The power electronic BDCs are derived from boost and buck unit. The boost derived converter are current fed converters and offers advantages in terms of inherent voltage gain, short circuit protection and lower input current ripple. The voltage spikes across switches, high rated device selection, hard switching, snubber and auxiliary circuit requirements are some of the undesirable factors. This occurrence happened due to unbalance power transfer by the power electronics converter. Similarly, voltage fed converter offers good voltage control during power transfer.

Keywords: Electric vehicles (EVs), high switching frequency (HSF), high electromagnetic interference (EMI), power electronic

Introduction

It is expected that by 2030, EV will be the largest mobile power source [1–3] and hence, it can be consider as a DES. Considering battery technology, one of the challenging part in EV is the charging and discharging of high density battery packs. Since the battery is considered as a load, power electronics converter with dc output is...
suitable for chargers. The typical power flow between battery and source for on-board chargers. In general, in charging process, grid voltage is firstly converted into a dc voltage through a PFC unit and transfers power to an isolated or non-isolated power electronic converter. If power flow from the converter is only towards battery, it is known as unidirectional converter. However, considering present demand and features BDCs are most famous since they allow reverse power flow, i.e. from battery to source. In EVs, area is main constraint where the on-board is to be placed. Therefore, high power density chargers are preferable. Based on the converter configuration and battery charging strategy different MOSFETs are considered [4]. For HSF operation of the converter, to maintain minimal switching rise time and fall time is a challenging task. For above considerations, a new GDC is proposed in the work to operate the proposed BDC topologies. The typical power flow between battery and source for on-board chargers is shown in Fig. 1

![Figure 1: Basic power flow between grid and EV](image)

It is clear from Fig. 1, the input and output of investigating converters having DC behavior. In EVs, area is main constraint where the on-board is to be placed. Therefore, high power density chargers are preferable. Based on the converter configuration and battery charging strategy different MOSFETs are considered [4]. For HSF operation of the converter, to maintain minimal switching rise time and fall time is a challenging task. For above considerations, a new GDC is proposed in the work to operate the proposed BDC topologies.

**DC-DC Converter**

The dc-dc converter regulates the fixed dc to a variable dc according to the application requirements. The prominent features of dc-dc converters are high voltage gain, high power density, and wide power regulation. The classification of dc-dc converters are shown in Fig. 2. Typically, UDC allows power flow from source to load, however in BDCs, power flow between source and load. The further classification of dc-dc converter is based on the input to the source

![Figure 2: Classification of DC-DC Converter](image)
EV battery chargers have gained lot of support across the globe in recent years. In the past decades, the EV charging infrastructures have been significantly increased. Still the EV battery and its charging infrastructure are challenging areas for prevailing the EV acceptance. It is expected that the EVs will be a larger source of energy in upcoming years. In order to integrate EV batteries to utility grid, a bidirectional converter configuration is necessary. In addition to the power converter, a battery configuration is required to coordinate with the power transfer from dc-dc converter during charging and discharging according to the battery charging state. Therefore, to develop a bidirectional dc-dc power electronic converter for charging/discharging of EV batteries becomes necessary. The aim of the work is to investigate the topological architecture of various high switching frequency BDC in electric vehicular applications. In this contrast, an isolated current fed BDC and voltage fed BDC are proposed and investigated. Since, the topological development requires high switching operation. Hence, a GDC is proposed tested experimentally in laboratory environment

**High Frequency Gate Driver Circuit**

Owing to the advancements in BDC designs and the availability of advanced MOSFETs (Si, SiC, GaN). Research into GDC is crucial for MSF (250-500 kHz) and HSF (≥500) [5-7]. Typical complicating factors in GDC design include the cost, noise sensitivity level, switching frequency, and range of gate-to-source voltages [8, 9]. The literature does not make any commendable attempt to offer a general GDC design. A simple approach to design is also not accessible everywhere and necessitates data collection in one specific spot [10, 11]. Industrial grade gate drivers are too expensive for academic usage because of their application-specific behaviour [12]. If you want to drive an HSF gate, you can add resonate components to provide pulses, but it will make your system more complicated and less reliable [13]. In contrast, developing GDCs is a tedious and laborious process because to the restricted resources available, and it is particularly difficult when it comes to HSF applications [14]. By applying a bipolar voltage across the gate-source terminal, a GDC may achieve far better results than one based on unipolar driving [15]. Why? Because bipolar switching means less switching losses and shorter turn-off times [16]. With this in mind, a number of initiatives have focused on creating bespoke bipolar gate drivers from existing components for use in a range of applications [17,18]. But most of these efforts are tailored to particular applications, are difficult and costly to implement, and lack a comprehensive, step-by-step process for creating BDCs.

**Isolated Current Fed Bidirectional Converter**

In order to operate converter by keeping its features such as high power density, proposed GDC in the work will play a significant role. Therefore, converter switching losses should be minimum [19] while operating for higher frequencies several techniques to achieve soft switching in-term of ZVS and ZCS have been developed for converter configuration [20]. The dead-band in DAB plays an important role to safeguard converter from short circuit [21]. Besides, VSC requires high turn ratio transformer in comparison to CSC [22]. The isolated CSC having benefits over VSC in the terms of natural high voltage gain, short circuit protection, and easy control. However, voltage spike across switches, high input current for inductor charging, hard switching are the prior concern for CSBD2C . The main reason for voltage spikes is the input inductor, which discharges through the reactive element of converter. The voltage spike across the switch is caused by the switch parasitic, which also acts as a sink for the energy from the inductor. To stabilise the converter's functioning, the topology incorporates a snubber circuit, which consists of an active and passive clamping circuit. The operating complexity and number of components in the converter are both increased by passive snubbers. For the input boost converter unit, the number of snubber elements is decreased in [17]. When the number of passive components increases, the operation becomes more compliant, which in turn reduces the converter's efficiency. You may replace the converter's active and passive snubber elements with a single auxiliary circuit, as described in. In order to address the high input issue, the symmetric converter architecture is used in [34]. The power that circulates between the capacitors makes it less suited, since the voltage distribution across the secondary side is affected. By adjusting the number of switches on the secondary, the centre mid-tapped transformer and voltage doubler circuit eliminate voltage unbalance while keeping voltage gain constant. Problems with CSC converters include a large number of components, inefficient power conversion because of hard switching, and an increased voltage spike in the absence of a snubber and other auxiliary components. To address the issues with the BD2C stated above, ICF-BD2C are designed to charge electric vehicle batteries with a tiny current injection...
rather than a big current. An interleaved converter topology increases the converter's rating for voltage and current by connecting several converter modules in series or parallel. Superior control over switches and converters is the outcome of these modules interacting with one another. Factors governed by the IEC, battery manufacturers, and fundamental electrical theory determine the charging current of the battery. The potential difference between the converter's output and the voltage at the battery's terminals is a key component in optimising the charging current. Consequently, an RSB system represents a promising alternative, with the goal of providing a clever answer to the problem of dependable and rapid charging for electric vehicle systems. Connecting low input batteries in series causes RSB to generate a potential difference, which in turn causes the dc-dc converter's soft switching function to fail. The BD2C reconfigurable, on the other hand, has worse efficiency, more voltage stress across power components, and no soft switching, in addition to increased switching losses. More circuit components and a smaller soft switching range were the results of efforts to address these issues. Reduced efficiency, increased component count, voltage clamping via auxiliary networks, loss of soft switching under light load conditions, and poor battery charging current are all consequences of the RSB in ICF-BD2Cs.

**Isolated Voltage Fed Bidirectional Multi-port Converter**

These converter topologies evolved in a sequential fashion, culminating in a MIMO converter, often called an MPC [46]. In electric vehicle applications, these MPCs allow for the charging of two batteries at once. Disconnecting the power supply and batteries is necessary for this particular electric vehicle use [47]. Because of the need to generate both positive and negative polarity voltage across the transformer, converters based on the DAB configuration—also called the H-4 configuration—are gaining popularity for chargers [48]. To produce voltage on both sides of the transformer in MIMO systems, optimal switching operation is necessary due to the leakage inductance of the transformer, a critical component of power flow [49]. The number of active switches in MIMO is increased by these DAB and TAB adjustments, and then their separate functioning at HSF is addressed [50]. Half bridge CSC (HBCSC), sometimes called the H-6 configuration, replaced DAB, resulting in the smallest amount of devices. Higher voltages are produced during the switching transition when these converters are operated with phase-shifted pulse width modulation and a 50% duty cycle hard switch [51]. The converter's switching losses determine the converter's efficiency. For this reason, the researchers have advocated for the use of the soft switched MIMO converter in EV scenarios. When two batteries of different voltages are charged at the same time, the demand for DAB rises. Once again, converter circuit PWM operation becomes complicated as the number of DAB grows, making transformer design and power flow management more problematic. Despite the researchers' introduction of MP topologies derived from current-fed boost converters, EV applications do not favour non-galvanic isolation between battery sources. Although the VFC design for multi-port applications is suggested in [58], the charging of low batteries cannot be controlled by PWM operation. For active switches, this PWM operation enables zero-voltage switching. But converters can only be used in systems that charge one battery at a time. According to the research in DAB, TAB, and HBC, MIMO converters have a lot of problems, including complicated switching, a large number of switches, and difficulties charging two different voltage batteries at once.

**High Frequency Gate Driver Circuit for EV Applications**

An EV-friendly high-frequency GDC is suggested in this study. In order to attain a high power density, the suggested GDC works between MSF (>=100 kHz) and HSF (<=1 MHz). We begin by suggesting several changes to the HSF converter's GDC and the criterion for choosing its components. Because of its low component count and straightforward design, the proposed GDC is both economical and dependable. Second, alternative competent driver circuits that are currently on the market are compared to the proposed GDC. The quantitative evaluation is based on power losses, cost, and dynamic switching performance. When compared to the chosen, commonly used gate drivers, the suggested GDC proves to be the most effective. Lastly, we describe the results of empirically validating the distinguishing properties of the proposed GDC for many test instances.

Any power electronic converter would be incomplete without power electronic devices with a high switching speed. Intricate considerations like as cost, on-state resistance, rise time, fall time, maximum working voltage, and current are involved in the application-specific device selection process. When it comes to managing high-
frequency fields (HSF) in the hundreds of kHz range, MOSFETs perform better than any other device. This makes them perfect for use in electric vehicle chargers and energy storage systems. However, in high power applications such as HVDC, traction motors, propulsion, and roller mills, among others, MOSFET's power handling performance is less impressive. On the other hand, MOSFETs are appropriate for applications involving electric vehicles and energy storage that fall within the 30-100 kW range. Notably, wide band gap devices, such as SiC, are gradually supplanting traditional Si switches as a result of technological advancements in this area. This is because these devices have superior switching characteristics, quicker settling times, and reduced losses.

Bidirectional DC-DC converters are essential components in electric vehicles (EVs) and hybrid electric vehicles (HEVs) for interfacing components in electrical powertrains. They are used for interfacing energy storage devices, such as batteries, with the main power bus of the vehicle.

Bidirectional DC-DC converters can transfer power in both directions, making them suitable for regenerative braking applications, where power is given to the wheels of vehicles during driving and received during braking.

Another study has investigated the use of soft-switching converters with two series half-bridge legs to reduce voltage stress of active switches, which can increase the efficiency and reliability of the DC-DC converter.

In summary, bidirectional DC-DC converters are essential components in electric vehicles and hybrid electric vehicles for interfacing energy storage devices with the main power bus of the vehicle. They are used for regenerative braking applications and can transfer power in both directions. Recent research has focused on designing bidirectional DC-DC converters with soft switching for electric vehicles, which can improve the efficiency and reliability of the power conversion system.

**Current Fed Bi-directional dc-dc Converter**

The HSF GDC has been proposed and its experimental results have validated its performance. In this chapter, an isolated current fed converter topology is proposed and performance is analyzed. It is investigated that the major challenges in a current source isolated bidirectional dc-dc converters are low conversion efficiency, high component count, hard-switching, narrow operating range, and high voltage spikes. To alleviate these problems, a current-fed soft switched naturally clamped isolated bidirectional dc-dc converter for vehicular applications is proposed. The proposed converter is an amalgamation of a current source half-bridge boost circuit at the input, and a voltage doubler at the output, interconnected through a HFT. Commercially available half-bridge modules can be directly employed for the building of the proposed converter making it industry-ready. A wide range for ZVS of power switches is achieved through the resonant tank composting of the resonant capacitor and transformer self-inductance. The proposed converter clamps the switch voltage naturally. Besides, ZCS turn-off for diodes is achieved in charging operation. Finally, simulation results and experimental measurements emphasizing feasibility of the proposed converter are presented.

Designing bidirectional DC-DC converters for electric vehicles comes with several challenges that need to be addressed to ensure optimal performance and efficiency. Some of the key challenges include:

- **Power Density and Efficiency**: Bidirectional DC-DC converters in electric vehicles require high power density and conversion efficiency to meet the demands of the vehicle's powertrain. Designing converters with improved circuit topologies and control strategies is crucial to enhance power density and efficiency.

- **Circuit Topology Design**: The choice of circuit topology plays a significant role in the performance of bidirectional DC-DC converters. Optimizing the circuit design to minimize losses, reduce voltage stress on components, and improve overall efficiency is a critical challenge in converter design.

- **Temperature Management**: Bidirectional DC-DC converters must effectively manage heat dissipation to prevent overheating and ensure reliable operation. Designing converters with proper thermal management techniques is essential to maintain performance under varying load conditions and environmental factors.
Voltage Transformation: Electric vehicles operate with varying voltage levels, requiring bidirectional DC-DC converters to efficiently transform voltage while maintaining stability and reliability. Ensuring that the converter can handle the voltage transformation requirements of the vehicle's electrical system is a key challenge in design.

Component Selection and Integration: Selecting the right components, such as power switches and inductors, and integrating them effectively into the converter design is crucial for achieving high performance and reliability. Careful consideration of component characteristics and their impact on converter operation is essential in the design process.

Addressing these challenges through innovative design approaches, advanced control strategies, and efficient thermal management techniques is essential to develop bidirectional DC-DC converters that meet the stringent requirements of electric vehicles for optimal performance, reliability, and efficiency.

In order to guarantee good performance and efficient power transmission, electric vehicle bidirectional DC-DC converters must meet stringent power density standards. In order to maximise the converter's power handling capabilities while minimising its size and weight, a high power density is necessary. The converter's input voltage should be 700–800 V, taken from a three-phase Vienna rectifier, and its output voltage should be able to give rated power to an electric vehicle's battery. It should also be able to handle high power levels. To meet the specifications for DC charging stations, the converter has to be modular so that single power stage converter units may be paralleled and the output power throughput increased.

In order to decrease the quantity of copper required for rapid charging, increase power density, and decrease the size of the magnetics, the converter has to run at high switching frequencies. The converter may accomplish soft-switching commutations, which decrease switching losses and increase efficiency, when it operates at high switching frequencies. Smaller inductors, made possible by high-frequency switching, may boost power density while decreasing heat solution and saving a tonne of money.

The search results do not specifically state the usual power density range for electric car bidirectional DC-DC converters. Nevertheless, the search results clearly show that power density is a major factor to consider when designing DC-DC converters for EVs. In order to improve the effectiveness of electric car regenerative braking and speed control, a new tri-mode bidirectional DC-DC converter is suggested. Achieving a high power density and efficiency were key design goals of the converter. In a similar vein, a universal DC-DC converter with a high power density is introduced for charging electric vehicles. The architecture of the converter makes use of an LCL-T resonant network and a single stage isolated bidirectional DC-DC converter. Power quality, efficiency, and density are all goals of the converter's design.

In electric cars, the power density of bidirectional DC-DC converters is affected by a number of variables, including the architecture of the converter, the switching frequency, the power semiconductor devices used, and the cooling system. An increase in power density is possible with the use of wide bandgap semiconductors and higher switching frequencies, for example, SiC and GaN. On the other hand, the converter's complexity and expense are raised by these considerations. Bidirectional DC-DC converters for EVs must therefore take into account a trade-off between efficiency, cost, power density, and reliability.

After conducting a comprehensive investigation into bidirectional DC-DC converters with soft switching for electric vehicles, several key conclusions can be drawn:

Efficiency Improvement: Soft switching techniques, such as ZVS (Zero Voltage Switching) and ZCS (Zero Current Switching), significantly enhance the efficiency of bidirectional DC-DC converters. This improvement is crucial for electric vehicles where energy conservation is paramount.

Reduced Switching Losses: Soft switching mitigates switching losses by minimizing the overlap between voltage and current waveforms during the switching transitions. As a result, converters experience lower losses and higher efficiency.

Enhanced Reliability: The reduction in switching stress on power semiconductor devices prolongs their lifespan and improves the reliability of the converter. This is particularly advantageous in the demanding automotive environment where reliability is essential.
Improved Power Density: Soft switching techniques allow for higher switching frequencies without significant losses, leading to smaller passive components and thus higher power density. This compactness is beneficial for electric vehicles with limited space for power electronics.

Bi-Directional Operation: Bidirectional converters with soft switching facilitate efficient energy transfer between different voltage sources, such as the battery and the motor drive, enabling functions like regenerative braking and battery charging.

Cost Considerations: While soft switching techniques offer numerous advantages, they may involve additional circuit complexity and cost. However, advancements in semiconductor technology and manufacturing processes are gradually reducing these costs, making soft-switching converters increasingly viable for mass adoption in electric vehicles.

Future Research Directions: Further research could focus on optimizing control strategies for bidirectional DC-DC converters with soft switching to maximize efficiency under various operating conditions. Additionally, investigating the integration of advanced materials and component technologies could lead to even more significant improvements in performance and cost-effectiveness.

Conclusion

Bidirectional DC-DC converters with soft switching hold immense potential for enhancing the efficiency, reliability, and power density of electric vehicles. While challenges such as cost and complexity remain, ongoing research and technological advancements are steadily addressing these issues, paving the way for the widespread adoption of soft-switching converters in the automotive industry.

References