Radius: Journal of Science and Technology
Volume 1, Issue 1, (2024) 241005 (11pp)

Comprehensive Review of Power Electronic DC-DC Converters in Electric Vehicle Applications

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Abstract: The rapid rise of electric vehicles (EVs) presents a sustainable alternative to traditional internal combustion engine (ICE) vehicles, significantly reducing greenhouse gas emissions and improving overall vehicle efficiency. This paper investigates the critical role of power electronic converters, especially DC-DC converters, within EV powertrains. Emphasizing the necessity of achieving appropriate voltage levels for battery and motor operation, it explores conventional and advanced DC-DC converter topologies, including the conventional boost converter (BC) and the interleaved four-phase boost converter (IBC). Additionally, the paper highlights the growing importance of wide bandgap semiconductors (WBGSs) such as silicon carbide (SiC) and gallium nitride (GaN) in enhancing converter performance by enabling higher switching frequencies, improved thermal operation, and reduced losses. Through a comprehensive analysis, the study reveals the potential of WBGSs to improve the efficiency and reliability of EV charging systems, power converters, and electric motors, making them crucial for future EV advancements. This work aims to underline the importance of power electronic converter design and control in shaping the future of electric vehicles.

Keywords: Transportation electrification; Electric vehicles; Power converters; Third harmonic injection; Multi-level inverter

1. Introduction

The past decade has witnessed a surge in the electric vehicle (EV) market, driven by their eco-friendliness, ample resources, and status as counterparts to traditional gasoline-powered internal combustion engine (ICE) vehicles. Notably, in 2020, the transportation sector contributed 27% of total greenhouse gas (GHG) emissions in the US [1]. Opting for electrified automobiles over conventional ones emerges as a compelling choice due to their ability to address issues associated with GHG emissions from traditional vehicles. Furthermore, electrified cars enhance efficiency, acceleration, overall performance, while simultaneously eliminating harmful GHG emissions and reducing maintenance costs [2].

A comparative analysis between EVs and ICE vehicles, focusing on an 845 km inter-city journey time, revealed that based on current battery capabilities, power charges exceeding 400 kW are necessary to achieve comparable travel times between the two types of vehicles [3]. The proposed solution to this challenge involves the utilization of high-speed chargers (XFCs)

Received: 28 September 2024 | **Revised:** 18 October 2024
Accepted: 22 October 2024 | **Published Online:** 27 October 2024

capable of providing at least 800 V direct current (DC) at the output [4]. The entire power supply system of an EV is divided into three segments: (i) the battery charging system, (ii) the powertrain, and (iii) regenerative braking, as illustrated in Figure 1. In this system, a specific DC-DC converter may be required for integrating individual energy sources into the high-voltage (HV)-DC bus of the EVs and plug-in hybrid electric vehicles (PHEVs) powertrain [5]. Looking ahead to 2023, a critical aspect in developing EVs lies in the battery charging system. This system charges all input sources, such as batteries and supercapacitors, via an AC–DC rectifier from the three-phase AC grid. The EV charging system, known as conductive charging, is broadly categorized as onboard and offboard charging systems. Onboard chargers are internal to the EV, while offboard chargers are external to the vehicles [6].

In the EV powertrain, each electric input source is connected to a high-voltage DC (HV–DC) bus via its own DC-DC converter, which powers the main load, the three-phase electric motor (EM) [7]. The primary load of the EV, the three-phase electric motor (EM), draws power from this HV–DC bus via a three-phase inverter. The voltage level of the EV's HV–DC bus typically falls within the range of 400–750 V. When propelling the EV with an EM sourced from electric batteries, a DC-DC voltage becomes imperative as the batteries' output voltage is notably lower than the EM's required voltage. To propel the EM, a traction inverter is essential, converting the DC batteries into variable-frequency alternating current (AC) [8]. Yet, an alternative viewpoint suggests raising the output AC voltage level of the inverter using a high-voltage transformer instead of a DC-DC converter, leveraging advantages like reliability, cost-effectiveness, compact size, and reduced weight—making DC-DC converters prime candidates for EV and hybrid electric vehicle (HEV) power trains [9].

Addressing drawbacks in charging power converters, wireless power transfer, energy storages, and electric motors can be achieved through the application of wide bandgap semiconductors (WBGSs) such as gallium nitride (GaN) and silicon carbide (SiC) based devices [10]. WBGS-based power converters, encompassing rectifiers, DC-DC converters, and inverters, offer numerous advantages, including higher switching frequencies, enhanced temperature operation, and lower losses compared to their silicon counterparts. Published wireless charging systems for electric vehicles, buses, fleets, and trucks, with power levels ranging from 50 kW to 500 kW, have demonstrated efficiency levels around 91–97%, emphasizing the role of WBGS semiconductor devices [11]. In motor drives, the use of WBGS semiconductor devices yields advantages such as low switching and conduction losses, high power density, lower ON-state resistance, and high-temperature operation [12]. This review explores a comprehensive comparison among GaN, SiC, and Si, highlighting the dominance of WBGSs due to faster switching frequency, reduced losses, and increased efficiency over silicon semiconductors. The current commercial progress positions silicon carbide (SiC) and gallium nitride as the most promising WBGS options today [13].

Chargers, whether onboard or offboard, serving EVs are high-power converters facilitating AC to DC and DC to DC power conversions. These converters act as the crucial interface directing the required power to be stored in batteries, sustaining the operation of an EV. Therefore, understanding the charging characteristics of the converter topology, control methods, thermal attributes, switching losses, and efficiency becomes paramount for the proper functioning of EVs, intricately linked to the power system demand scenario. This paper seeks to underscore the significance of power electronic converters and their control in forecasting electric vehicle applications. This HV–DC bus through a three-phase inverter which drives the EM [14]. Here, the voltage level of this HV–DC bus of the EV is around 400–750 V. Moreover, moving the EV via an EM from electric batteries, a DC-DC voltage is required because the batteries' output voltage is much lower than the required voltage of EM. A traction inverter is needed to drive the EM by converting the DC batteries into variable-frequency AC. However, a disagreement could be made for stepping up the output AC voltage level of the inverter by utilizing a high-voltage transformer instead of a DC-DC converter. This is due to it having several essential advantages, such as reliability, cost-effectiveness, compact size, and lightweight DC-DC converter appears to be an excellent candidate for EV and HEV power trains [15].

Furthermore, the demerits of the charging power converters, wireless power transfer, energy storages, and electric motor can be overcome by utilizing wide bandgap semiconductors (WBGSs), such as gallium nitride (GaN) and silicon carbide (SiC) based devices [16]. Numerous advantages, including higher switching frequencies, higher temperature operation, lower losses, etc., can be achieved by WBGS-based power converters, such as rectifiers, and DC-DC converters and inverters, over silicon semiconductor device-based power converters [17]. In several wireless charging systems with 50 kW, 60 kW, 100 kW, 200 kW, 250 kW, and 500 kW power levels were published for electric vehicles, buses, fleets, and trucks with and without wide bandgap (WBG) semiconductor devices. They have also depicted that the efficiency of these wireless charging systems remains around 91–97%. In motor drives, several advantages, such as low switching and conduction losses, high power density, lower ON-state resistance, and high-temperature operation, can be achieved by utilizing wide band gap semiconductor devices [18]. Moreover, this review paper discusses the comparison among GaN, SiC, and Si with the current status, challenges, and different WBG semiconductor trends. The comparison showed that the WBGSs provide tremendous advantages, such as faster switching frequency, lower loss, and higher efficiency over silicon semiconductors [19]. Due to these characteristics and the commercialization progress of silicon carbide (SiC) and gallium nitride, they are considered the most promising WBGS nowadays.

Onboard and/or offboard chargers that are utilized are high-power converters, where AC to DC and DC to DC power conversion occurs. These converters are the interface that channels required power to be stored in batteries to run an EV. Thus, information regarding charging characteristics of the converter topology, control method, thermal attributes, switching losses, and efficiency is vital for the EV to work properly, which is, in fact, directly related to the power system demand scenario. Therefore, this paper aims to value the importance of power electronic converters and their control in the forecast of electric vehicle applications.

2. DC-DC Converter

Attaining the ideal voltage level is crucial for the functioning of electric vehicles (EVs), since excessive power can cause harm to the gadget, while inadequate power makes it nonfunctional. In order to tackle this difficulty, a DC-DC converter is utilized for the purpose of mitigation [20]. In electric vehicle (EV) installations, the voltage levels of battery storage and supercapacitors (SCs) often fall within the ranges of 250–360 V and 150–400 V, respectively. On the other hand, electric motors require an operating voltage of around 400-750 V, which is much higher than the voltage levels of batteries and supercapacitors. Therefore, it is necessary to incorporate a high step-up voltage DC-DC converter into electric vehicle powertrains in order to increase the voltage levels of the battery and supercapacitor. Figure 1 depicts the categorization of DC-DC converter configurations, highlighting the light-blue alternatives that are acknowledged for their suitability with electric vehicle powertrains because of their advantageous performance characteristics [21]. For a thorough examination and evaluation of various DC-DC converter structures, which encompass methods for increasing voltage, as well as their uses and efficiency, refer to reference [22].

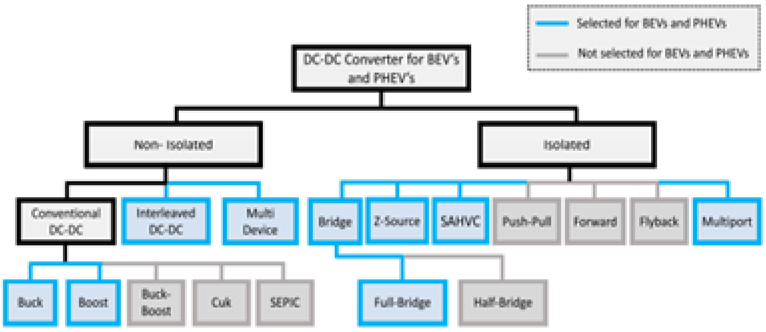

Figure 1: Classification of DC-DC converter topologies [6]

2.1 Conventional Boost DC-DC Converter (BC)

Figure 2 depicts a conventional step-up or pulse-width modulation (PWM) boost converter setup. It consists of a DC input voltage source (Vs), an energy storage component (inductor and capacitor), a controlled switch (such as MOSFET or IGBT) represented as Q, a diode D, a filter capacitor C, and the load (electric motor). The output voltage of a boost DC-DC converter continuously surpasses the input voltage, which justifies its classification as a "Boost" converter [23]. The typical boost converter provides several benefits, including simple circuitry, cost reduction due to fewer components, effective filtering for electromagnetic interference, and good overall efficiency [24]. However, the converter has limits in attaining a substantial increase in voltage. Extra precautionary steps are required to prevent short circuits, necessitating a parallel configuration of power-switching devices to manage high power. Furthermore, the system demonstrates significant size and mass as a result of employing a sizable capacitor to eliminate output voltage fluctuations. Maintaining a consistent output voltage in the face of fluctuations in the input power source presents a significant obstacle. The presence of nonlinearities, such as bifurcation, multiple equilibrium points, periodic behavior, and chaos, inherent in DC-DC converters makes it challenging to design a high-performance control system for them [25]. There are two main types of controllers: voltage mode controllers and current mode controllers. The extensive advantages of current mode controllers have led to their ubiquitous usage in DC-DC converters [26].

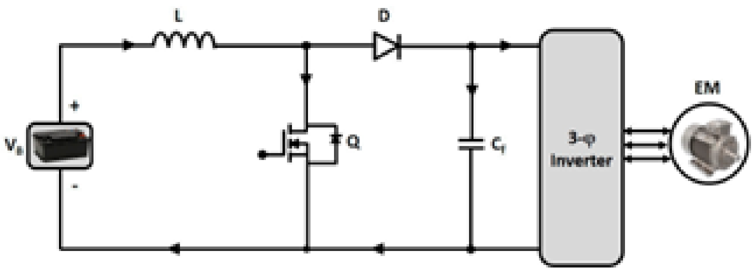

Figure 2: Conventional Boost DC-DC Converter [27]

The study described in reference established sophisticated control system design methods for typical DC-DC boost converter topologies, with the goal of tackling intrinsic difficulties. The investigated cutting-edge techniques comprise sliding mode control (SMC) [27], model predictive control (MPC) intelligent fuzzy logic/control systems and fractional-order proportional-integral-derivative (FOPID) control systems [28]. Every solution has distinct benefits to address the problems related to traditional DC-DC boost converters. The SMC approach exhibits resistance to changes in internal parameters, insensitivity to external shocks, rapid reaction to transitory conditions, and the capacity to quickly improve resilience against nonlinear uncertainty. Meanwhile, Model Predictive Control (MPC) demonstrates exceptional proficiency in incorporating state variables and input limitations during the design stage, successfully overseeing control of the conventional DC-DC converter. Due to their efficiency, simplicity, practicality, and ease of tuning, fuzzy logic-based PID control systems are extensively utilized [29].

2.2 Interleaved Four-Phase Boost DC-DC Converter (IBC)

The interleaved boost converter, depicted in Figure 3, incorporates parallel boost or step-up converters to evenly distribute the current over a parallel link. By dividing the current, power losses are minimized and current strains are efficiently reduced [30]. The interleaved four-phase boost DC-DC converter (IBC) is equipped with four identical inductors (L1, L2, L3, L4) distributed throughout four step-up levels. The objective of this design is to reduce the weight of the conductor and minimize fluctuations in input current. It achieves this by using four power-switching devices in parallel to sequentially shift the phases, together with diodes and a filtering capacitor to eliminate fluctuations in the output voltage. The IBC design utilizes unique magnetic cores in each inductor to maximize energy storage and release. This allows for the amplification of the voltage level by almost four times [31]. The four-phase interleaved boost DC-DC converter is highly preferred for electric vehicles (EVs) because it allows for smaller inductors and output capacitors, significantly reduces input current and output voltage ripples, and improves the overall efficiency of the system [32].

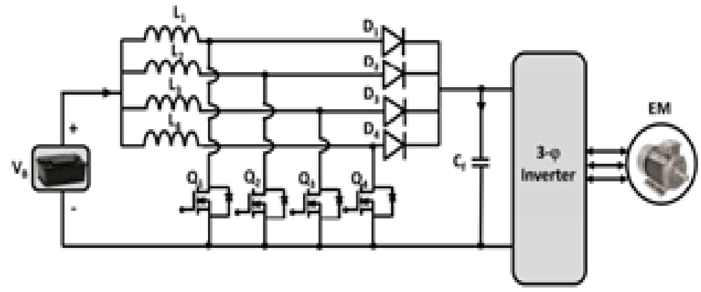

Figure 3: Four-phase Interleaved DC-DC Boost converter [33]

Although the IBC has advantages, it is sensitive to changes in the duty cycle, incurs large expenses, and may have an influence on the magnetic core when load alterations occur [34]. Several improved control strategies have been suggested to stabilize the interleaved multi-phase boost converter against notable disturbances [35]. The mentioned control techniques are model predictive control fuzzy controller, sliding mode control (SMC) and PI hybrid controller, high-order sliding mode control (HOSMC), and active disturbance rejection control (ADRC) [36]. A significant advancement occurred with the introduction of a sophisticated hybrid Super-

Twisting (ST) ADRC dual-loop controller. The ST-ADRC controller demonstrated resilience against variations in input voltage and load disturbances, improved accuracy in voltage tracking, and a more significant decrease in both recovery time and voltage fluctuations when compared to traditional control systems. The implementation of the converter was demonstrated to greatly improve the control performance, as evidenced by [37].

2.3 Boost DC-DC Converter with Resonant Circuit (BCRC)

Conventional boost DC-DC converters commonly use hard switching, resulting in higher switching losses in battery electric vehicle (BEV) and plug-in hybrid electric vehicle (PHEV) powertrains. In order to tackle this problem, DC-DC converter topologies utilize a soft-switching architecture to minimize switching losses. Soft-switching is a technique where the voltage or current across the switch reaches zero when it is being turned on or off. As a result, when the voltage and current are multiplied together, the outcome is zero, leading to no power losses. By minimizing switching losses, the converter is able to operate at high switching frequencies, resulting in a reduction in the size of the heatsink and overall volume of the converter [38]. Figure 4 depicts the soft-switching arrangement of the boost DC-DC converter with the resonant circuit. It consists of two switching devices: the primary switch Q1 and the auxiliary switch Q2.

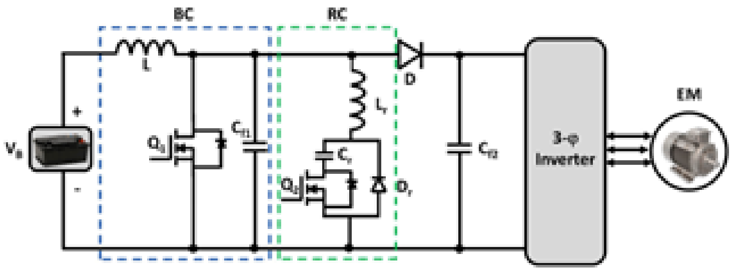

Figure 4: DC-DC Boost Converter with Auxiliary Resonant Circuit [6]

The soft-switching architecture, in conjunction with the resonant circuit, offers a safeguard against irregularities in load power, hence guaranteeing elevated safety requirements. Nevertheless, it is important to mention that the Boosted Resonant Circuit (BCRC) is not compatible with high-power electric vehicle (EV) powertrains and does not have bidirectionality support. Soft-switching techniques are recognized as the most efficient method for improving efficiency and reliability in electric vehicle DC-DC converters by reducing switching losses [39]. The challenge of building a control system for soft-switching DC-DC converters stems from the requirement of accurately controlling many switches and timing that depends on the load.

A robust control approach is necessary for the soft-switching DC-DC converter of an electric vehicle to address transitory needs such as voltage matching, power transfer, and response time in the face of system uncertainty. It is essential because the converter needs to function properly when there are unpredictable changes in the load of electric vehicles. The study described in the reference examined and executed an analysis of a proportional-integral (PI) controller for a soft-switching boost DC-DC converter that incorporates an auxiliary resonant circuit. By doing simulations and experiments, it was confirmed that the controller greatly enhanced the efficiency of the system. A separate study conducted in [40] examined various time domains between PI and fuzzy logic controllers for soft-switching bidirectional DC-DC converters in electric vehicles. The results indicated that the fuzzy controller had superior performance compared to the PI controller during the settling and peak overshoot rise.

2.4 Isolated ZVS DC-DC Converter (ZVSC)

In order to meet the demands of isolation, cold beginning, and soft switching, it is necessary to utilize an isolated zero-voltage switching DC-DC converter (ZVSC). The configuration of a standalone Zero Voltage Switching Converter (ZVSC) is depicted in Figure 5, showcasing a dual half-bridge architecture on both ends of the transformer. Each power-switching device in this setup is equipped with a parallel capacitor to enable soft-switching. The ZVSC, which is isolated, has several benefits such as a simple control technique, improved efficiency, natural soft-switching without the need for extra circuitry, higher power density, fewer components, compact packaging, and a lightweight design. Crucially, it prevents actual device rating repercussions in comparison to conventional full-bridge DC-DC converters [33].

Nevertheless, despite these advantages, ZVS converters are not suited for high-power electric vehicle (EV) applications that surpass 10 kW. This constraint derives from the lack of a tolerance operation and the presence of high voltage stress across the power-switching devices. In order to manage the total current flowing through the switches (Q1-Q4), it is necessary to divide the DC capacitors (C1-C4). Furthermore, the inclusion of a bigger capacitor is necessary in order to effectively reduce the fluctuations in the output voltage, as indicated by references.

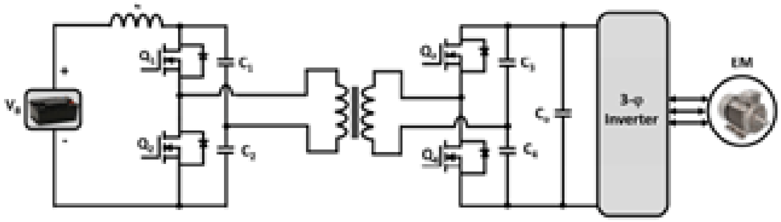

Figure 5: Isolated Zero Voltage Switching (ZVS) DC-DC Converter [33]

3. Conclusions

The continued evolution of electric vehicles (EVs) hinges on the optimization of power electronic converters, particularly DC-DC converters, which play a pivotal role in ensuring the efficient integration of various energy sources within the powertrain. The comparison of conventional and advanced converter topologies is given in Table 1 which reveals that while traditional converters like the boost DC-DC converter offer simplicity and cost-effectiveness, advanced designs such as the interleaved four-phase boost converter provide superior efficiency and reduced power losses. Furthermore, wide bandgap semiconductors (WBGSs), especially silicon carbide (SiC) and gallium nitride (GaN), are proving to be transformative in elevating converter performance, offering significant gains in terms of switching speed, thermal endurance, and overall system efficiency. As EV technologies progress, the deployment of WBGS-based power converters will be key to overcoming challenges related to power management, thermal regulation, and system reliability, thus accelerating the global transition toward sustainable transportation.

Table 1: Topologies, functions, merit and demerit of DC-DC Converters

Topology	**Controllability**	**Bi-directionality**	**Reliability**	**Power Range**	**Efficiency**	**Merits**	**Demerits**
BC	High	Not Present	Moderate	High	Low	• Simple Circuit • Low-Cost • Simple control technique	• Larger filter size • Higher Ripple Rate • Low Voltage Gain
IBC	High	Not Present	Moderate	High	Moderate	• Low Input Current • High Voltage gain • Low filter size • Simple control technique	• High switching losses • High components current
BCRC	High	Not Present	High	High	Low	• Low heat sink size required • Soft switching • Low EMI	• Low voltage gain • Not suitable for higher power application
ZVSC	Moderate	Not Present	High	Low	High	• Low switching issues • Low EMI • High Power rating	• Gates have high current rating • Cannot tolerate fault • Larger filter size

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