Comparative analysis of DC-DC converter architectures for electric vehicle battery charging applications

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ABSTRACT

The rise of Electric Vehicles (EVs) offers a promising solution to mitigate the environmental and health impacts of traditional gasoline-powered cars. This paper provides an in-depth this involves analysing and comparing various data sources of DC-DC converter topologies, identifying key features and areas for improvement. The goal is to guide automotive industry researchers in selecting the optimal DC-DC converter topology to achieve high-power density. By continually enhancing DC-DC converter design and evaluation, hence this can improve the EV performance, efficiency, and sustainability. This will reduce dependence on fossil fuels, lower carbon emissions, enhance air quality, and pave the way for a greener, more sustainable transportation sector.

Keywords: Electric Vehicle (EV), Direct current (DC), Inductor-Inductor Capacitor (LLC), Pulse-width modulator (PWM).

1. INTRODUCTION:

The electric vehicle has gained attention within the automotive industry. Emphasizing the eco-friendly aspects of EVs, this leads to zero tailpipe emissions and reduces greenhouse gas emissions. Highlighting the energy efficiency of EVs, this converts about 60-70% of the electrical energy from the grid to the power the wheels. Focusing on the cost saving of EVs includes lower operating costs and reducing maintenance costs. Advanced electronics and software that control and optimize EV Performances, efficiency, safety. EVs represent a significant evolution in the automotive industry, driving innovation, transformation, and so on. [1]

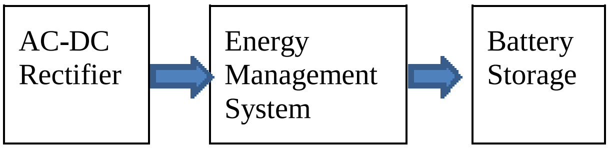


Figure 1: Basic Electric Vehicle System

EVs, which use electricity as the primary source and provides various benefits to customers, including zero emissions, low operating lost, smooth & quiet ride, reduced maintenance ,instant torque and acceleration. Overall, EVs offer a unique combination on performance, efficiency and sustainability that benefits customers and the environment. The EV system consists of three importance parts namely;[14]

a) Storage unit
b) Control unit
c) Propulsion unit[5]

a) Storage units: The battery pack or energy storage system that powers the EV. It stores electrical energy, i.e., it is used to propel the vehicle.

b) Control unit: This refers to vehicle control (VC) or Electric Control Unit (ECE). It Manages & regulates the electrical and energy flows between the energy Storage Unit, propulsion Unit and other Components.[15]

c) Propulsion unit: This refers to an electric power train. It consists of electric motors, power electronics and transmission. It converts electrical energy from the process involves converting an energy storage unit into mechanical energy for propelling the vehicle forward. The EV charging system consists of rectifier unit to convert the AC power from the grid or charging Station into DC power required by battery pack or energy Storage System. The overall performance or efficiency of a battery module depends not only on the design but also on how the battery modules charged and used. Nowadays, Power converters are widely utilized because of its merit. The preliminary merit of using SMPC is the possibility of minimizing the increase the switching frequency to reduce both conduction loss and switching loss. [3]

2. METHODOLOGY :

The converter has two topologies namely;
1. LLC resonant converter
2. Phase-shift full bridge converter.

The study uses simulations and analysis to achieve the goal of High efficiency and true soft switching (Reducing switching losses and stress on components). The MOSFET has three terminals: Gate (G), Drain (D) and Source(S). The drain and source terminals act as a switch contact and terminal Gate used for control the device. The gate terminal has full control over the MOSFET conduction. There are two power transistors namely BJT-Bipolar Junction Transistor and MOSFET [9]. MOSFET has advantages over BJT for high frequency application and MOSFET have switching speed multiple times compare to IGBT of similar rating and size.

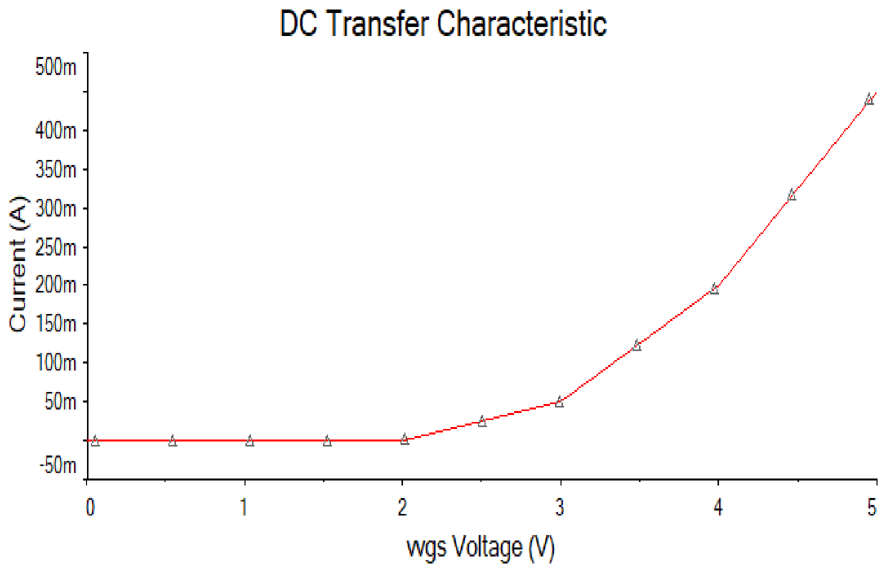


Figure 2: Characteristics of the MOSFET

BJT is a current-controlled device and it has a large base current (I_b), while MOSFET has voltage controlled device hence it operates at high frequency but BJT is opposite to it. Figure 2 shows the relationship between I_d verses V_{ds} for different values. The drain current (Id) did not increase significantly as gate current increases from zero. When V_{gs} (gate to source voltage) exceeds a threshold value, the MOSFET is in ON state and the threshold value varies from 2 volt to 4 volt. When the V_{gs} value is less than V_{th} (threshold voltage) it means MOSFET is turning off and it also called as cut-off region. [6]

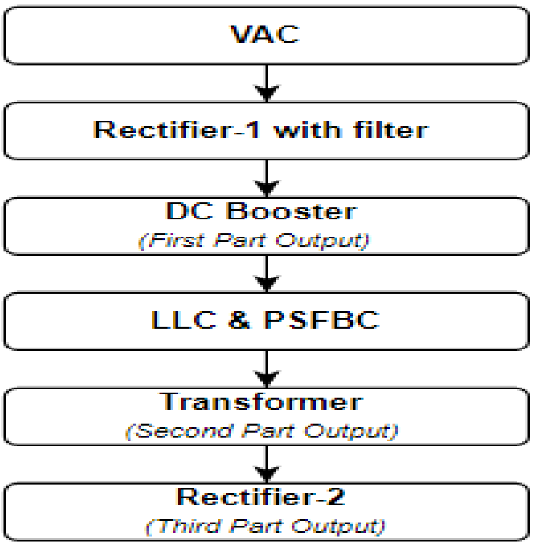


Figure 3: Block diagram of the proposed system.

2.1 AC-DC Converter:

From Figure 3, there are two rectifiers, rectifier 1- is used to convert available power or grid source to DC power and rectifier 2- used to convert from transformer secondary(AC)to the output (DC). To achieve a low ripple factor and high efficiency. For rectification purposes, diodes are used hence it is uncontrolled rectifiers. To obtain a smooth and constant output waveform from the rectifier output, the load must be a resistive. In the charging system, the ripple factor plays a major role but ideally the ripple factor should be in zero in output waveform as;

Ripple factor $=I_{o\ (ac)}/P_{ac}$

$= \sqrt{((I^2_{rms}/I^2_{dc})-1)}$

2.2 DC Booster:

The DC booster is essential for the battery characteristics because the batteries are always designed for high voltage. To gain this battery cells connected in series. These converters reduce cell count and increase voltage, a technique commonly used in charging systems. [10]

2.3 LLC Resonant Topology:

Resonant converters are a cutting-edge power supply topology that has attracted significant attention. These converters have become increasingly popular across various applications owing to their exceptional performance, which yields:

- Enhanced power efficiency
- Reduced component count
- Minimized electromagnetic interference (EMI).

As illustrated in Figure 4, the primary objective of this topology is to achieve zero voltage switching (ZVS) in Phase Shifted Full Bridge converters at high frequencies. This soft switching technique is a hallmark feature of resonant converters.

Zero-voltage turn-on is achieved by using the energy stored in the leakage and series inductance of the transformer to discharge the output capacitance of the switches through resonant action. [12]

To archive zero voltage

$0.5\ L_s I^2_1 > 0.5(C_3+C_4)\ Vi^2 > 0.5 C_s Vi^2$

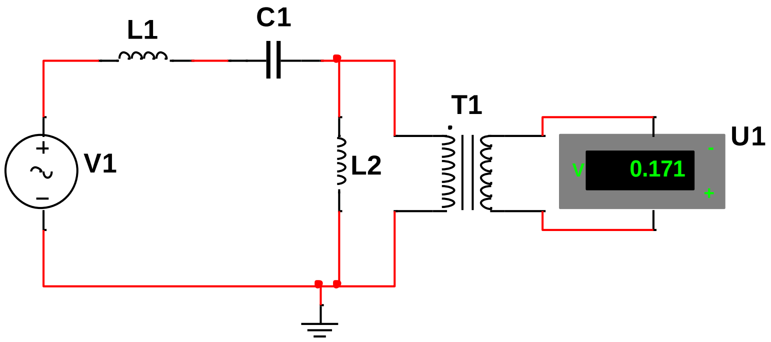


Figure 4: LLC Resonant Circuit

2.4 Pulse-width modulator (PWM) Topology:

Pulse-width modulation (PWM) is a technique used to regulate the amount of power supplied to a load by rapidly switching the power is either on or off. This approach avoids the energy losses associated with traditional linear power delivery methods [8]. PWM has some drawbacks:

a) Discontinuous power draw: The load receives power in pulses rather than continuously.

b) Non-contiguous energy delivery: The energy supplied to the load is not constant, but rather delivered in bursts. High-frequency Pulse Width Modulation (PWM) power control systems can be easily implemented using semiconductor switches. As mentioned earlier, these switches consume negligible power when fully on or off. However, during the brief transition periods between on and off states, both voltage and current are present, resulting in power loss in the switches. A PWM inverter uses a constant output waveform with polarity reversed periodically to achieve desired frequency, with input voltage controlled by adjusting pulse width.[11]

In the PWM inverter, the output waveform has constant amplitude whose polarity reverses periodically to provide the output fundamental frequency [4]. The source voltage is switched at regular intervals to produce a variable output voltage [7].

2.5 Phase Shifted Full Bridged Topology:

The phase-shift full bridge converter, depicted in Figure 3, is a highly promising topology for high frequency, high-power applications. This converter has several desirable characteristics, including high efficiency, ranging from 80% to 95%. Notably, it outperforms the half-bridge converter in terms of efficiency. The full bridge converter comprises four MOSFET switches. [2]

3. TYPES OF CONVERTERS:

In DC-DC Converters mainly there are two types' viz.

- Non-isolated DC-DC converter.
- Isolated DC-DC converter.

The non-isolated converter is of the following types.

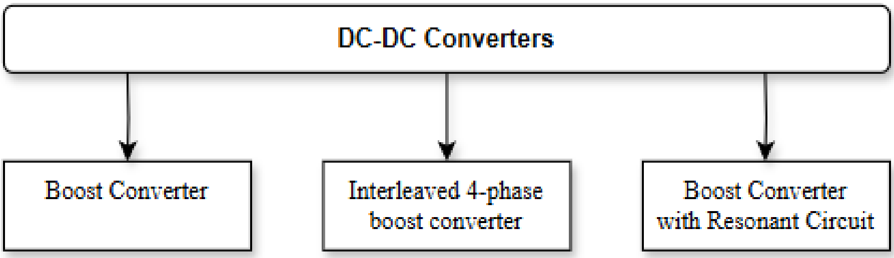


Figure 5: Types of DC-DC converter

Non-isolated DC-DC converters have a direct connection between input and output circuits, offering lower cost, smaller size, and higher efficiency compared to isolated models. They are commonly used in low-power devices and high voltage DC-DC converters[16]

3.1 Boost converter:

Boost converters, illustrated in Figure 6, are widely used in various electrical applications, particularly those requiring higher voltages. These converters typically use Pulse Width Modulation (PWM) control techniques, which offer relatively simple and easy-to-implement control circuits.

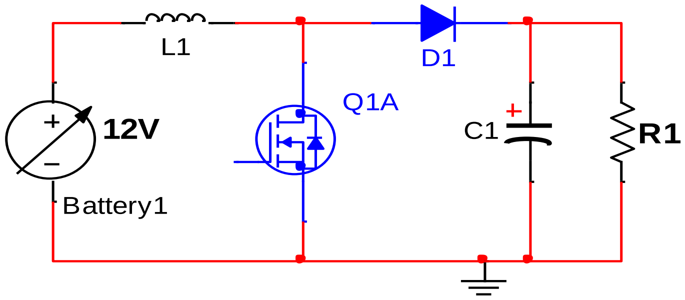


Figure 6: Boost converter.

The main purpose of boost converters is to increase the voltage while decreasing current, which reduces the strain on the input power source. [3]

Furthermore, by using transformers or other isolation components, boost converters can provide safe and reliable separation between the input and output, thereby enhancing overall system safety and dependability. Boost converters have some limitations, including power losses in the inductor and switch components, which can reduce the overall system efficiency. They can also experience output voltage fluctuations when dealing with changing loads, requiring effective control strategies to stabilize the output. Additionally, boost converters may not be suitable for linear loads, such as resistive loads, and can have varying physical characteristics. [13]. Boost converters are widely used in power electronic systems, including: Solar battery arrays, Electric vehicles, Power management systems, and other applications.

3.2 Interleaved 4-phase boost converter:

The interleaved 4-phase boost converter (IBC), shown in Figure 7, offers improved performance, efficiency, and stability by employing four identical levels with separate inductors and a continuous phase-shift. This structure enables multiple switches to operate simultaneously by distributing input and output currents among multiple branches. This approach reduces the current and voltage stress, increases power density, and minimize the output ripple current. [3] The benefits of IBC include improved efficiency due to reduced power losses, enhanced stability and reliability, higher power density, reduced output ripple current, improved electromagnetic interference performance.

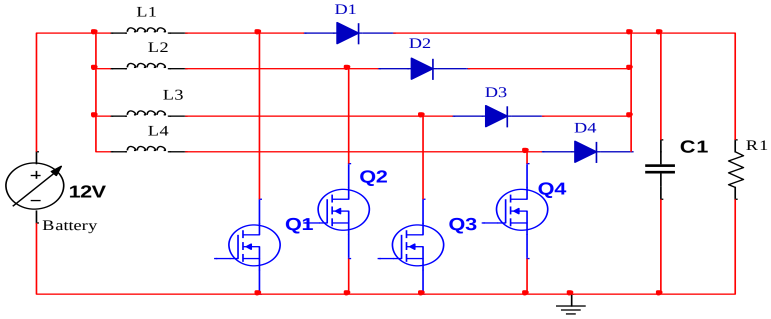


Figure 7: Inter leaved 4-phase DC-DC Boost converter.

However, the IBC also has some drawbacks: Increased complexity in the control circuitry. Higher hardware costs due to the requirement of multiple components. Potential increase in EMI due to higher switching frequency and phase coupling.

3.3 Boost Converter with Resonant Circuit:

The Boost Converter with Resonant Circuit (BCRC) is a widely used topology in power electronics. By incorporating a resonant circuit, the BCRC reduces the switching speed of the switches, thereby minimizing electromagnetic interference (EMI) and improving electromagnetic compatibility (EMC). Key benefits of the BCRC include adjustable output voltage through tuning of resonant circuit parameters, reduced EMI, and improved EMC.

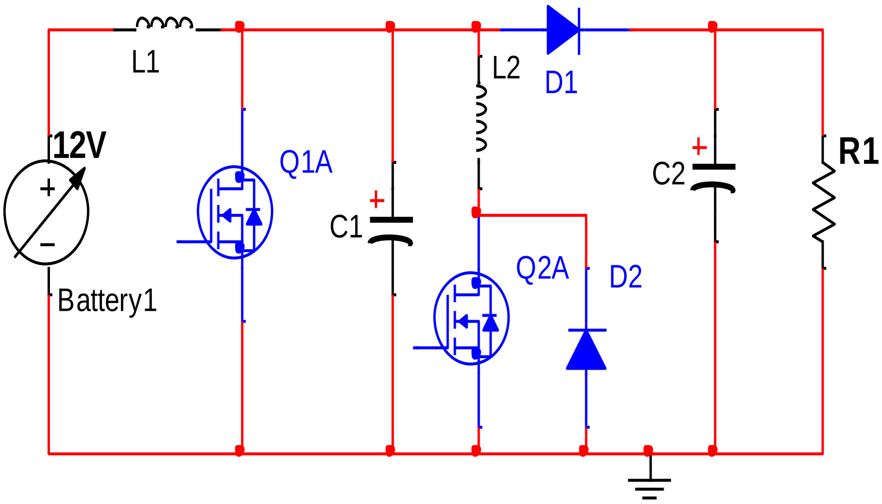


Figure 8: Boost converter with resonant circuit.

However, the BCRC also presents some challenges: a more complex design and analysis due to the resonant circuit. The resonant frequency, capacitance, inductance, and other parameters to ensure system stability and reliability. [2]

4. COMPARISONS BETWEEN DC-DC CONVERTERS:

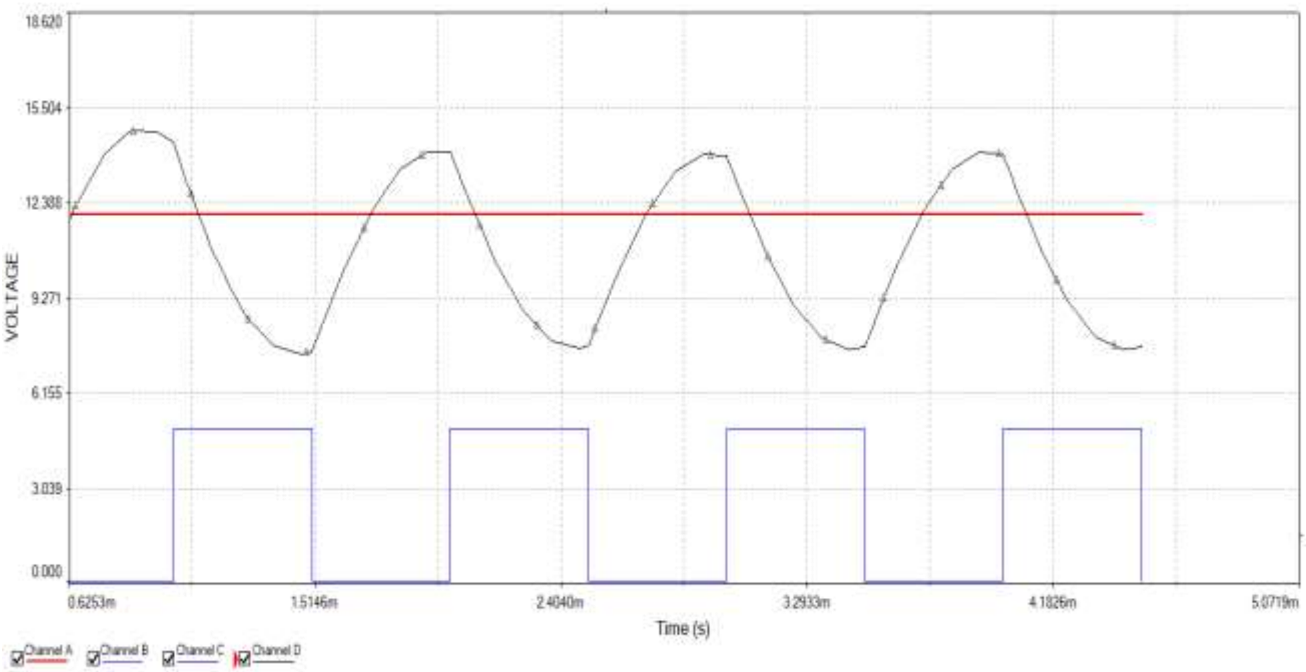
Table 1: Comparisons between DC-DC Converters

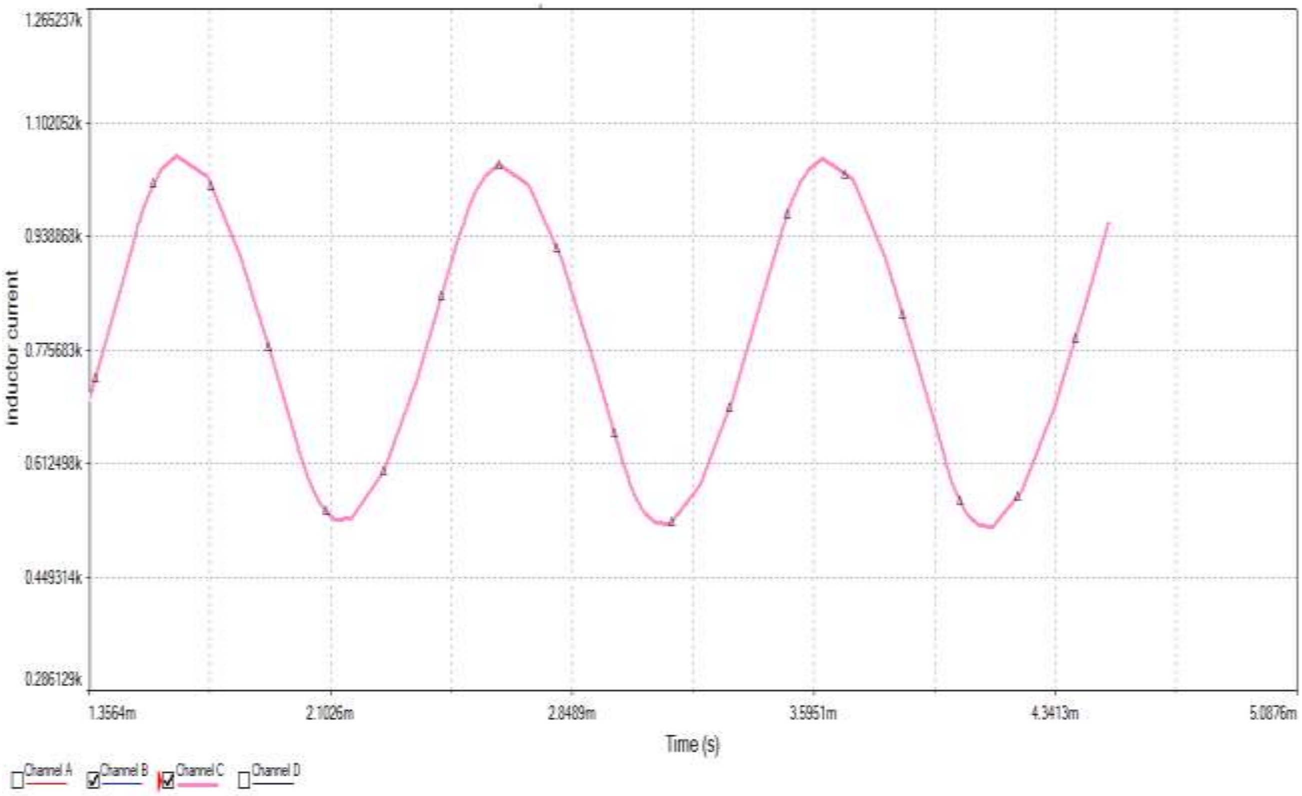
Converters	Advantages	Disadvantages
Boost converter	✓ Higher Output Voltage than Input Voltage. ✓ Simple Control ✓ Lower Input Current ✓ Input-Output Isolation	✓ Power losses ✓ Output voltage fluctuations ✓ Linear Load Limitations
Interleaved 4-phase boost converter	✓ High-power density ✓ Reduced output ripple current ✓ Reduced power losses in switches and inductor elements.	✓ Increased control ✓ complexity Increased cost ✓ EMI issues
Boost Converter with Resonant Circuit	✓ High efficiency ✓ Low electromagnetic interference ✓ Adjustable output Voltage	✓ Increased design complexity ✓ Resonant circuit stability

5. RESULTS:

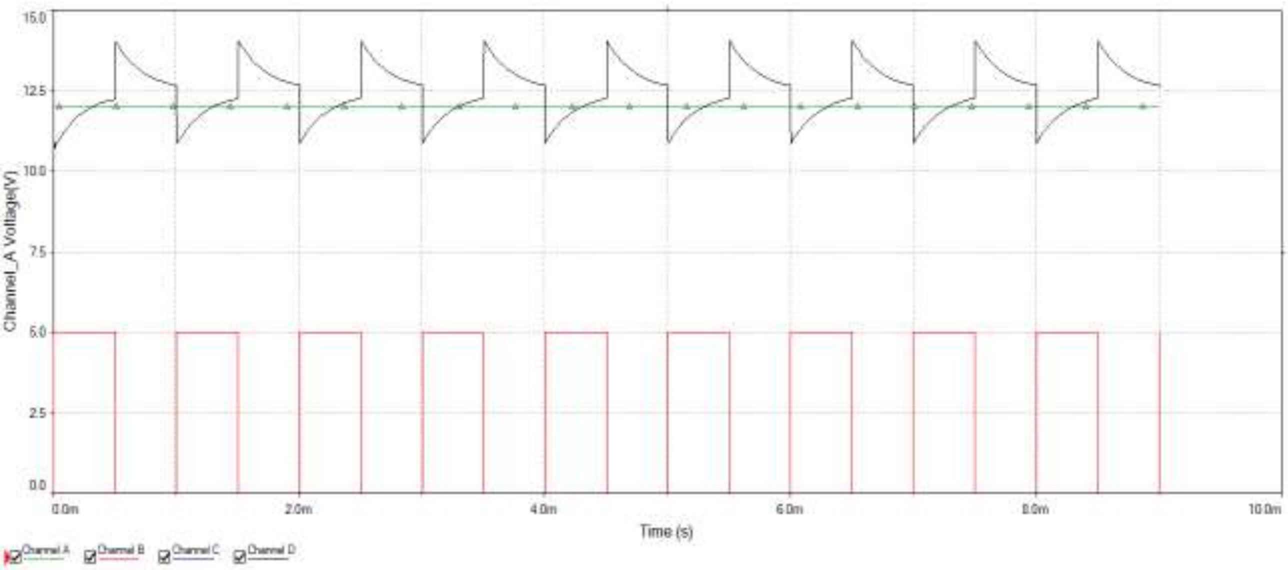
Different types of non-isolated DC-DC converter outputs

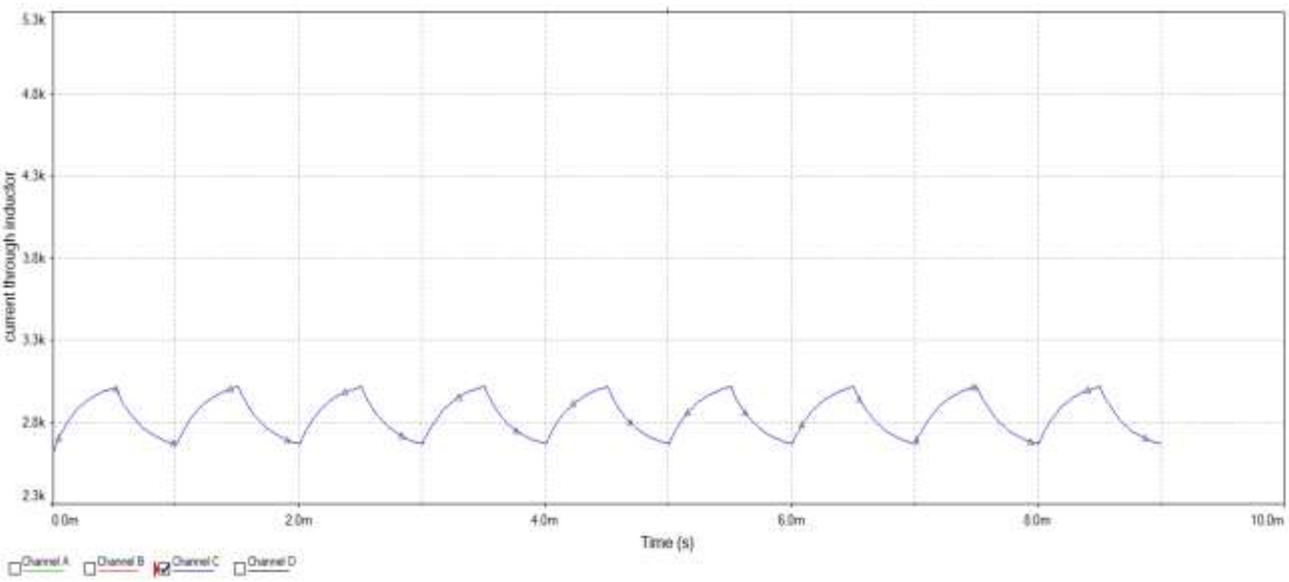
Boost converter



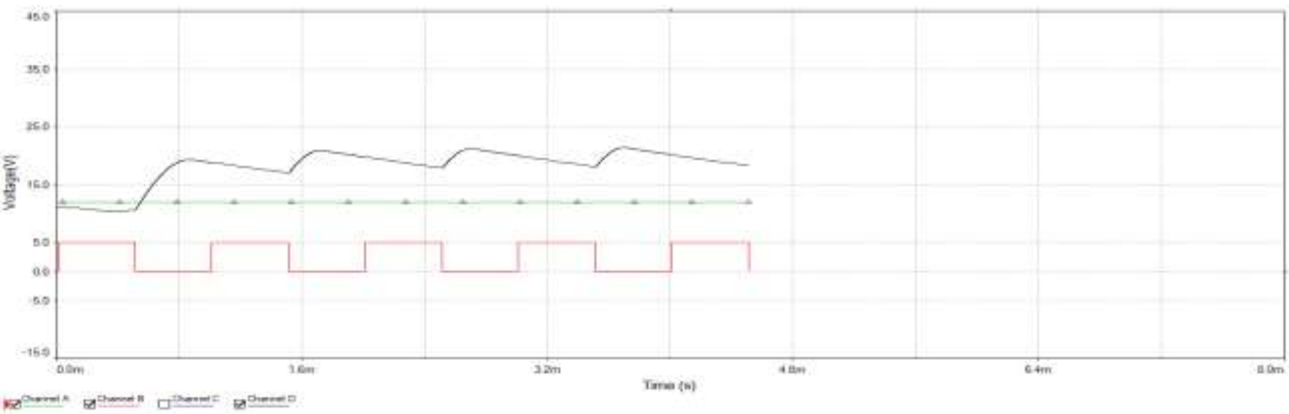


Interleaved 4-phase boost converters





Boost Converters with Resonant Circuit



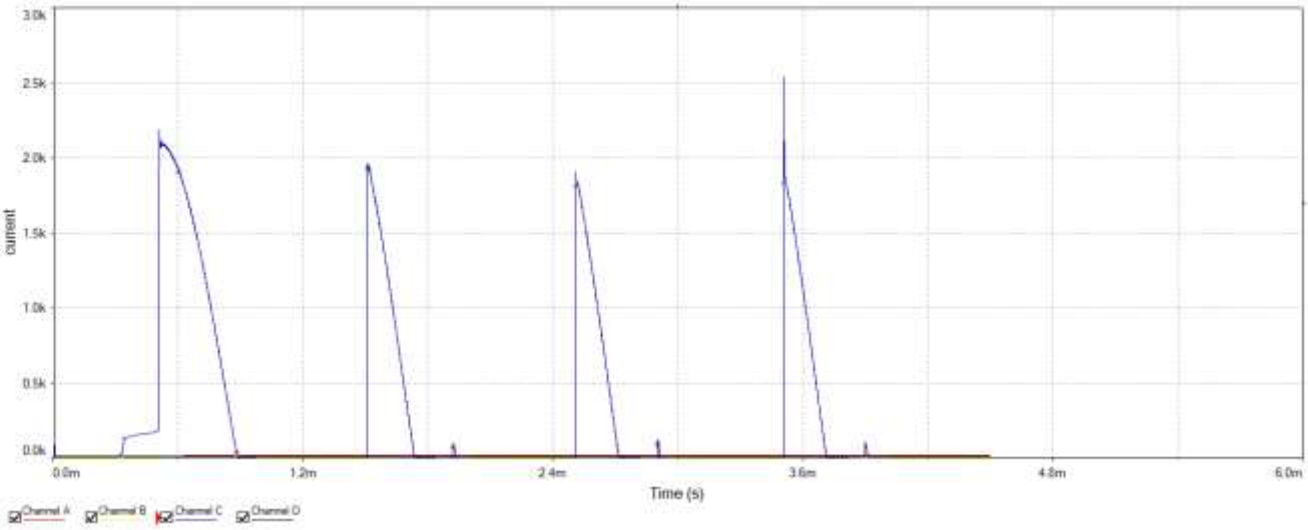


Table 2: Comparison of types of dc-dc converters with different outputs

Parameters and types of converters	**Boost converters**	**The interleaved 4-phase boost converter**	**Boost Converter with Resonant Circuit**
V_{in}	12V	12 V	12 V
Clock signal	5 V	5 V	5 V
V_o	14v	14 V	21 V
Current through the inductor	1000 mA	2860	2000

6. CONCLUSION:

DC-DC converters are essential in electric vehicles (EVs) as they convert DC voltage from the input power source to different DC output voltage levels. This paper provides an overview of the principles, types, and key components of DC-DC converters, as well as evaluation criteria and potential improvement strategies. When designing and selecting DC-DC converters, it is essential to understand the different types and their operating principles. To ensure system reliability and protection, protection circuits are recommended for overvoltage, over-temperature, and short-circuit conditions.

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