

Converters in Electric Vehicles: An Overview

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Abstract—Power electronic circuits, which consist of DC-DC converters, are essential components of contemporary electric vehicles. According to isolation schemes between the input and the output, DC-DC converters could be divided into two basic topologies: non-isolated converters and isolated converters. The isolated converter can provide isolation between its input and output and is widely used in situations where more than one output is needed. However, it has a larger size compared with the non-isolated one. And for vehicle applications, efficiency and size are the two most important aspects to be considered. Moreover, Isolated converters use a high-frequency transformer to isolate the input and the output side of the power conversion stage. Non-isolated converters are preferred due to lower losses, cost, size, and no core saturation-related problems. This paper briefly explains the recent developments and overall operation of Non isolated DC-DC converters used in electric vehicles.

Index Terms— Electric Vehicles, Non-Isolated Bidirectional DC-DC Converters, Integrated Converters, Interleaved Converters.

I. INTRODUCTION

The impact of fossil fuels on human health and the environment has become a major concern for environmentalists. The release of carbon dioxide and other greenhouse gases from fossil fuels has contributed significantly to global warming. The depletion of fossil fuels and fluctuations in crude oil prices are also major disadvantages. In response, governments are increasingly looking for cleaner forms of transportation, and electric vehicles (EVs) have emerged as a promising solution. EVs offer numerous advantages to their owners, including reduced costs of operation and maintenance and eligibility for government incentives. By switching to EVs, we can improve air quality, save fuel, and reduce noise pollution. Furthermore, the urgent need to stop using non-renewable resources and cut carbon emissions is critical in combating global warming. With EVs replacing internal combustion engines in automobiles, they are having a positive impact on the environment, as they produce significantly lower carbon emissions compared to traditional vehicles. Therefore, the adoption of EVs is crucial in addressing environmental contamination and reducing our carbon footprint.

Electric vehicles (EVs) are vehicles that are propelled by an electric motor that is powered by electricity that is stored in batteries. There are various EV varieties, each with special qualities and benefits. The most typical varieties are battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), hybrid electric vehicles (HEVs) and Fuel Cell Electric Vehicles (FCEVs).

Ref [1]. Non-isolated DC-DC converters are commonly used in electric vehicles because of their smaller size, lower cost, and higher efficiency compared to isolated converters. They are used to step-up or step-down the voltage of the battery to match the requirements of the electric motor, the on-board charging system, and other electrical loads in the vehicle.

Non-isolated DC-DC converters are essential components in contemporary electric vehicles. Some of the popular Non-isolated converter topologies are Buck, Boost and Buck-Boost converters. They are preferred over isolated converters due to their smaller size, lower cost, and higher efficiency. Buck-boost and boost converters are the most common types of non-isolated converters used in electric vehicles. Ref. [2] Advanced control techniques such as PWM can be used to optimize the operation of these converters and improve their efficiency. In this paper, a brief review of DC-DC converters used in Electric vehicles is presented. Section II presents an overview of Conventional Converters. Section III presents an overview of Integrated Converters and Interleaved Converters in EVs are discussed in Section IV.

II. CONVENTIONAL CONVERTERS

A. Buck Converters

Buck Converters are converters that are both simple and efficient. They step up the current to produce a low output DC voltage in a DC-DC configuration. To smooth out the discontinuous input current, a large capacitor is necessary for the buck converter to function properly. Ref. [3] A controlled DC output voltage can be obtained by using a buck converter to step down an unregulated DC voltage input. During operation, the input voltage is applied to the inductor 'L' when switch 'S' is turned ON, and power is then delivered to the load output. According to Faraday's law, the inductor current also increases. When switch 'S' is turned OFF, the voltage across the inductor 'L' reverses, and the freewheeling diode 'D' can be forward biased. This enables the energy stored in the inductor to be delivered to the load output. A capacitor 'C' can be used to smooth out the continuous current. By using an LC filter, the pulsating input can produce a smooth DC output voltage.

In EVs, a Single-Input Three-Output DC-DC Buck Converter is utilized to convert a single DC voltage input into multiple output DC voltage levels. Different voltage levels such as 5 V (for telemetry and microprocessor) and 12 V (for Headlight and Horn) are required in an EV and can be obtained from the non-isolated bidirectional DC-DC Buck converter. This topology has a single input and three output DC voltage levels and employs four switches to derive three outputs from a single input. Ref. [4] The non-isolated bidirectional SIMO DC-DC converter has four possible switching modes of operation. The efficiency and reliability of this topology are significantly higher than that of conventional DC-DC buck converters that are typically used for producing the various voltage levels required by EVs. Additionally, the utilization of this converter topology results in reduced cost and switching losses, while increasing the reliability and availability of the converter.

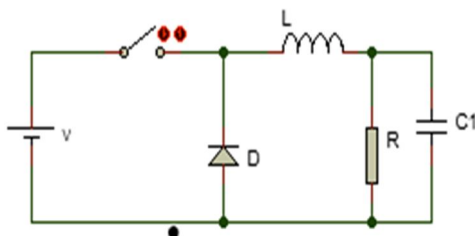


Figure 1. buck converter

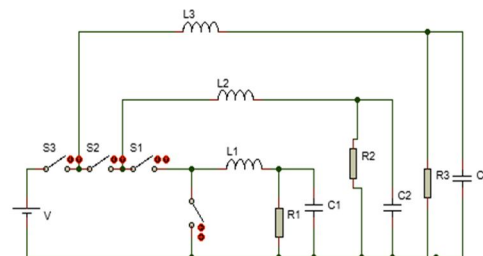


Figure 2. Single-Input three output DC-DC Buck Converter

B. Boost Converters

Boost converters are capable of generating an output voltage that exceeds the input voltage. These converters exhibit a continuous input current and a discontinuous output current, and they are equipped with freewheeling diodes that protect against reverse current. Compared to buck converters, boost converters have a lower implementation cost due to their use of a lower value input capacitor, lower current rating switch, and low side MOSFET driver. Ref. [2] A boost converter comprises a DC voltage source (V_{in}), an inductor (L), a controlled semiconductor switch (S), a diode (D), a capacitor (C), and a load resistance (R). Examples of semiconductor switches that can be used in boost converters include MOSFETs, IGBTs, and BJTs. During operation, when switch S is ON, the diode becomes reverse-biased, and the inductor current increases. When switch S is OFF, the diode becomes forward-biased, and the inductor current decreases, releasing energy stored in the inductor to the output circuit.

Single-input Multiple-output DC-DC Boost converter

Single-Input Multiple-Output (SIMO) DC-DC converters have been developed to efficiently reduce the number of electronic components required to obtain different output voltages, thereby reducing costs. Ref. [5] By

reducing the number of electronic components, SIMO converters can deliver various levels of output voltage required by the load from a single source of DC input voltage. These converters can uplift the voltage to a controllable middle voltage and high voltage DC output from a low voltage input power source. The SIMO DC-DC converter is comprised of two switches, S1 and S2, two diodes, D1 and D2, inductors, L1 and L2, capacitors, C1 and C2, resistive loads, R1 and R2, and a single input source, Vi. The operation of the SIMO boost converter is divided into four modes, depending on the switching behavior of its switching transistor.

High Gain Cascaded DC-DC Boost Converter

To ensure smooth operation of electric vehicles, a dependable DC-DC boost converter is required to deliver a stable voltage to the motor controller. An adapted cascaded DC-DC boost converter can achieve high gain with an intermediate duty cycle, reducing conduction loss and making it suitable for EV motor controllers and other renewable energy systems. The converter comprises of two active switches, which are controlled in a complementary manner for simplicity. The first stage includes two inductors (L4 and L5), three diodes (D9, D10, and D11), and a capacitor to amplify the input voltage. In the second stage, two inductors (L1 and L2) and three diodes (D1, D2, and D3) amplify the voltage, while the final stage employs two capacitors (C1 and C2) to amplify the voltage again. Finally, the L3 and C3 filters provide the output voltage [6].

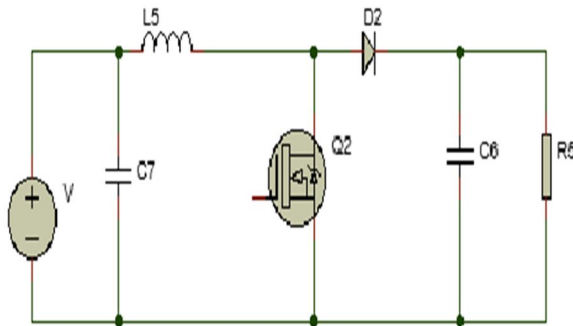


Figure 3. Conventional boost converter

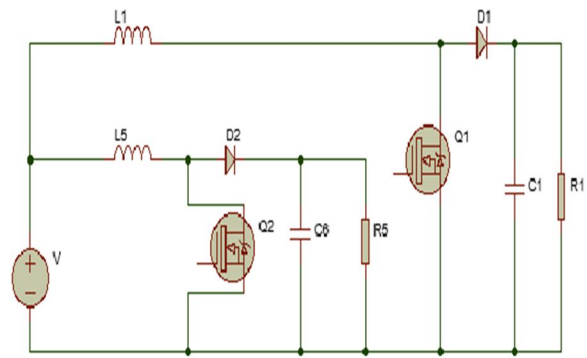


Figure 4. Single-input Multiple-output DC-DC Boost converter

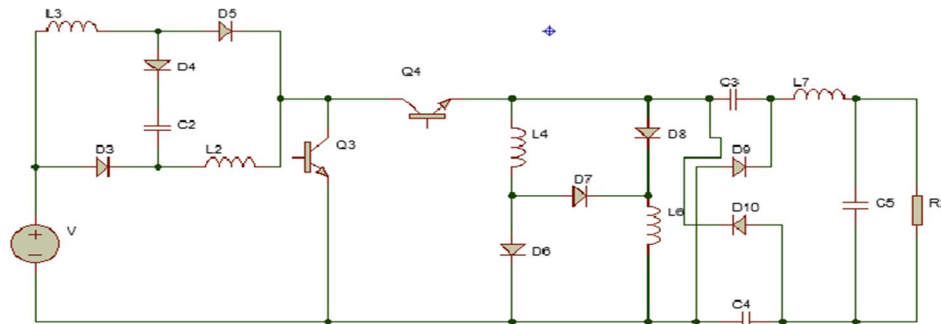


Figure 5. High Gain Cascaded DC-DC Boost Converter

C. Buck-Boost Converter

Buck-boost converters are essential components in the power electronics of electric vehicles (EVs). They serve as voltage regulators, stepping up or stepping down the voltage from the battery to match the voltage requirements of the various subsystems in the EV. This helps to improve the efficiency of power transfer and extend the range of the vehicle. Buck-boost converters are particularly useful in EVs because the battery voltage can vary widely depending on the state of charge, temperature, and load conditions. It has the least components, the highest reliability [7]. The non-inverting buck-boost (NIBB) converter topology is utilized to replace the boost modules of the FODB converter. This configuration offers a wider range of output voltages and a high voltage gain. Additionally, it allows the switches and capacitors to operate at a voltage lower than the output voltage, which results in a reduction of current and voltage ripples. The IPOS floating buck-boost converter is designed with two output capacitors that are always in series with the input voltage source, and each capacitor voltage is the output of a NIBB module.

A NIBB module has three modes of operation: Buck mode, boost mode, and buck-boost mode. However, the buck-boost mode is avoided in the operation of the proposed converter due to higher switching losses and larger inductor requirements, which lead to higher losses and larger ripple voltage in the output capacitor. The IPOS floating buck-boost converter consists of two NIBB modules and can be divided into two regions of operation: voltage step-down operation and voltage step-up operation. Ref.[8] In voltage step-down operation, both modules operate in buck mode with the same duty ratio but phase-shifted switching signals. In voltage step-up operation, both modules operate in boost mode with the same duty ratio but phase-shifted switching signals. During the transition from one region to another, the modules operate in a combination of both buck and boost modes to ensure a smooth transition. Operating one module in buck mode and another in boost mode results in lower efficiency compared to when both modules operate in the same mode.

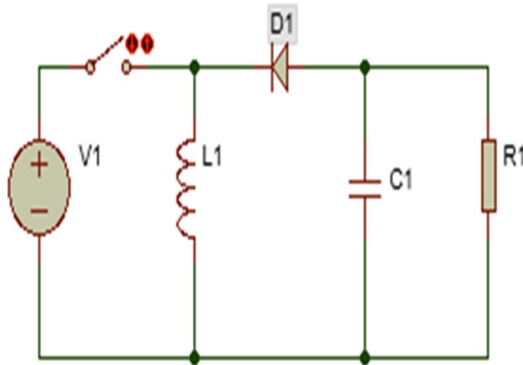


Figure 6. Buck-boost converter

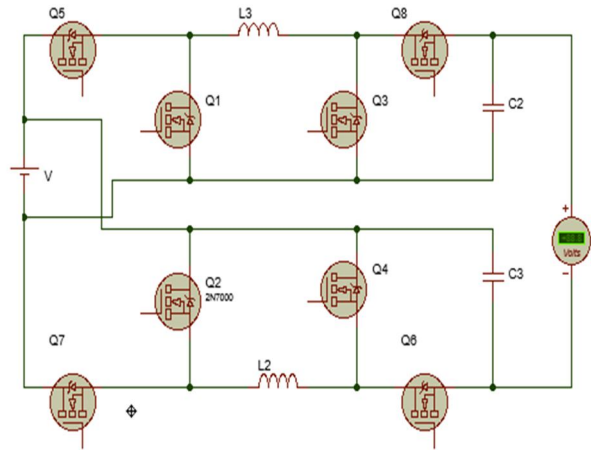


Figure 7. Input-parallel output-series (IPOS) floating buck-boost converter

D. SEPIC Converter for EV Battery Charging Applications

The SEPIC converter topology shares similarities with a non-inverting buck-boost converter. It comprises a switch, two inductors connected with a coupling capacitor. Nowadays, the SEPIC converter is preferred over the buck-boost converter due to its ability to provide output continuous current even when the input side is discontinuous. Designing a SEPIC converter involves using various passive and active components such as inductors, capacitors, and power electronic switches. Ref. [9] The advantages of SEPIC converters include lower ESRs, non-inverted load voltage and current, and minimized ripple. Mode 1 involves the switch S1 operating, with both L1 and L2 charging, and the coupling capacitor C2 discharging. In mode 2, the switch operates, and both inductors L1 and L2 discharge, while the coupling capacitor C2 starts charging.

E. Zeta Converter

The Zeta converter, a fourth-order DC-DC converter, is designed to function as a non-inverting buck-boost converter for battery charging applications in electric vehicles. Unlike conventional buck-boost converters, the input and output terminals of the Zeta converter share the same ground. The converter has a simple design, consisting of four energy storage elements: two inductors and two capacitors. An inductor at the output side ensures continuous and ripple-free output current. As a buck-boost converter, the Zeta converter is capable of both increasing and decreasing the output voltage without inverting it. It has a short settling time, low switching stress, and can be connected with high-frequency transformers. Ref.[10] The Zeta converter comprises a switch, a diode, two inductors, two capacitors, and a load. The converter can operate in two modes: on-mode and off-mode. The on-mode is activated when S1 is turned on and D1 is off, while the off-mode occurs when S1 is turned off and D1 is on.

III. INTEGRATED CONVERTERS

A. Reduced Component Buck-boost integrated converter

A control strategy based on current sensing has been implemented for plug-in electric vehicles. After conducting a literature review, it was found that a compact integrated buck-boost converter with a two-loop control strategy

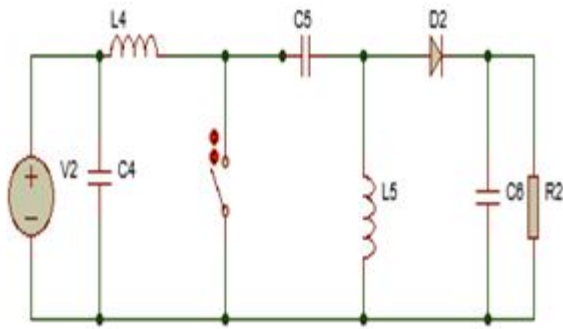


Figure 8. Sepic converter

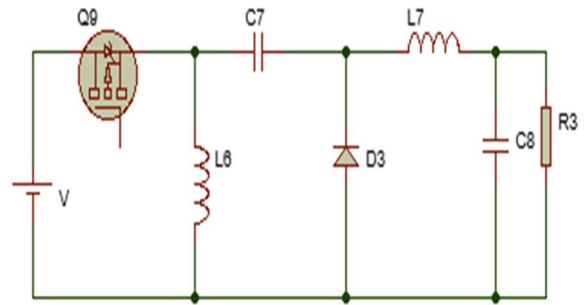


Figure 9. Zeta Converter

would be suitable for plug-in charging mode. This converter, which is designed to be compact and efficient, corrects the unity power factor on the grid side. The proposed system has a variety of applications, including electric cars, electric scooters, and electric bikes, and operates in three modes: Plug-in charging mode, propulsion mode, and regenerative braking mode. The buck-boost integrated converter with a two-loop control strategy has been developed specifically for plug-in charging mode [11].

B. High Gain Re-Lift Luo Converter with Buck Converter for Electric Vehicle Applications

The Integrated Re-lift Luo buck converter is designed to be used in Multiple Port Converters systems (MPCs) for various EV applications such as battery charging and supplying power to auxiliary loads. The converter integrates two conventional converters, Re-lift Luo and buck converters, and can provide both step-up and step-down outputs with minimal voltage ripple. The compact design of the converter does not require any electromagnetic devices such as transformers or coupled inductors. The RLBC can theoretically achieve a gain of up to 120 times for step-up operation. To achieve step-up output, the Re-lift Luo converter is used in the positive output, while the buck converter is integrated to generate step-down output. The Re-lift Luo converter increases the output voltage in two stages, with each stage increasing the voltage in a geometric progression. Ref. [12] This effectively enhances the output voltage transfer gain and increases the voltage gain of the converter for step-up output. The converter also has the capability to generate step-up and step-down voltages simultaneously, making it a single-input dual output (SIDO) converter.

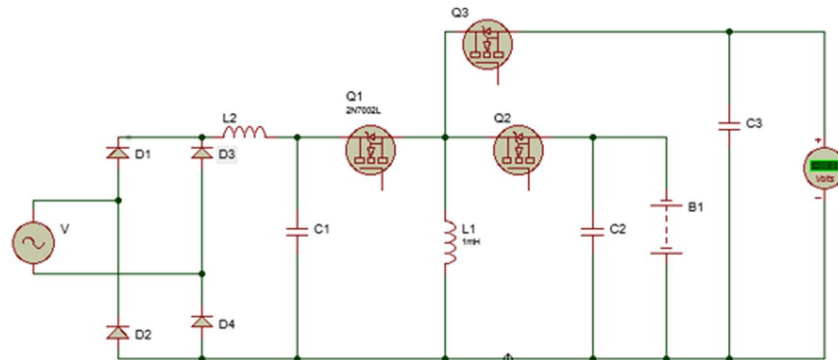


Figure 10. Reduced Component Buck-boost integrated converter

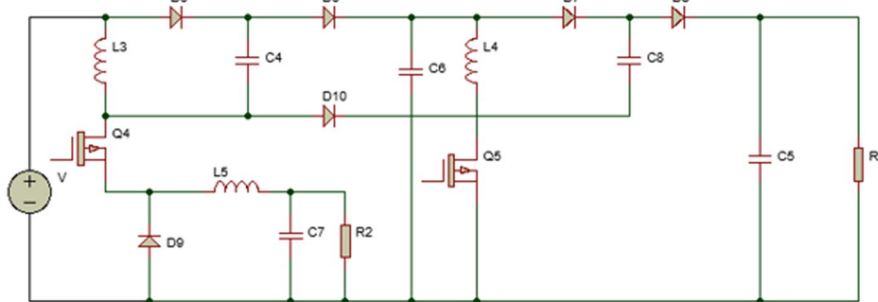


Figure 11. High Gain Re-Lift Luo Converter with Buck Converter for Electric Vehicle Application

IV. INTERLEAVED CONVERTERS

The interleaving technique involves connecting multiple switching cells together, which increases the effective pulse frequency by synchronizing smaller sources and operating them with a relative phase shift. This method improves power conversion and saves energy without affecting conversion efficiency. Utilizing the interleaving technique reduces output voltage ripples, resulting in decreased switching losses and improved efficiency. This technique can be applied to converters used in various automotive applications such as hybrid electric vehicles, ultracapacitors, batteries, photovoltaic systems, and fuel cell systems.

A. Bidirectional interleaved DC/DC converter

Typically, electric vehicles rely on a three-phase motor to provide the necessary traction force. A power conversion system composed of a DC/DC converter and a three-phase inverter is required to convert power from the battery to the motor. A bidirectional DC/DC converter is situated between the energy storage system and the inverter and can function in either boost-mode or buck-mode. During EV motoring mode, energy from the battery is transferred to the motor via the DC/DC converter and the three-phase inverter, which operates in boost-mode to drive the motor. During EV braking mode, regenerated energy from the motor is sent back to the battery, and the converter operates in buck-mode to charge the battery.

In boost-mode, the interleaved DC/DC converter is made up of two boost converter modules. The DC-link voltage is raised from the battery voltage through the use of two interleaved DC/DC converter boost modules. Each pair of IGBT switches on the same leg are triggered complementarily, and the battery discharges to supply the needed power in the DC link. The two modules equally share the battery current [13].

In buck-mode, the interleaved DC/DC converter is made up of two buck converter modules. The power flow is reversed from the motor to charge the battery, resulting in a negative DC-link current. As a result, the two currents flowing through the two buck modules of the DC/DC converter will charge the battery. The inductor currents will also be negative due to the power flow reversal. The current waveforms in CCM under buck operation are similar to those in boost-mode but with reversed current directions.

B. Interleaved Two-Leg Buck-Boost Converter in EV Charger Design

The ITBBC is capable of acting as a voltage regulator between an EV's battery and the grid-side AC-DC converter, eliminating the need for a voltage control loop and removing the 2-f ripple constraint from the system design. By doing so, overshoots/undershoots of the DC-bus voltage can be minimized without the use of a PI controller, allowing for a reduction in the size and cost of the DC-bus capacitor. When used as the back-end DC-DC converter of an EV charger, the ITBBC significantly reduces battery current ripples at a 50% duty cycle or minimizes them to almost zero. This feature reduces the stress on the EV battery during charging/discharging since the two inductor currents always flow in opposite directions, cancelling out the ripples when added to make the battery current. Ref. [14] These advantages improve the efficiency of the whole system, regulate the DC-bus voltage against variable battery voltage, and increase the battery lifetime.

The ITBBC plays a crucial role in a single-phase, bidirectional EV charger, which comprises two converters: the AC-DC converter (front-end converter) that regulates P and Q, and the ITBBC converter (back-end converter) that acts as a voltage regulator for VD against the variable battery voltage, VB. Compared to the conventional reversible non-isolated DC-DC converter, the ITBBC offers superior ripple reduction for all D values. By utilizing the ITBBC, the EV charger can operate optimally with excellent dynamic and steady-state responses, and lower battery stress.

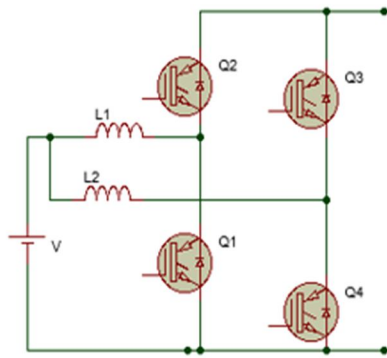


Figure 12. Bidirectional interleaved DC/DC converter

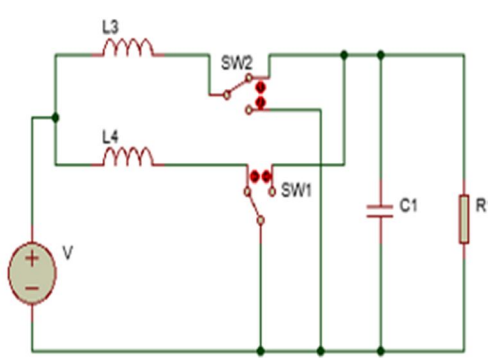


Figure 13. Basic ac model of an ITBBC

V. CONCLUSIONS

In conclusion, the use of power electronic circuits, specifically DC-DC converters, in electric vehicles is crucial for their efficient and effective operation. The two basic topologies of DC-DC converters, non-isolated and isolated, have their advantages and disadvantages. The choice of converter topology is dependent on several factors, including the need for isolation between input and output, efficiency, and size. Isolated converters are ideal for applications where multiple outputs are needed, while non-isolated converters are preferred for their lower losses, cost, size, and lack of core saturation-related problems. Overall, this paper has highlighted the recent developments and overall operation of non-isolated DC-DC converters used in electric vehicles. It is evident that these converters play a vital role in the efficient operation of electric vehicles. With further research and development in this field, it is expected that non-isolated DC-DC converters will continue to be a significant technology for electric vehicle power electronics.

ACKNOWLEDGMENT

We would like to specially thank Dr.Mrunal Deshpande, Associate Professor, Department of Electrical and Electronics, SSN College of Engineering for their constant support and guidance.

REFERENCES

- [1] H. Qiao, Y. Zhang, Y. Yao and L. Wei, "Analysis of Buck-Boost Converters for Fuel Cell Electric Vehicles," 2006 IEEE International Conference on Vehicular Electronics and Safety, Shanghai, China, 2006, pp. 109-113.
- [2] S. Dahale, A. Das, N. M. Pindoriya and S. Rajendran, "An overview of DC-DC converter topologies and controls in DC microgrid," 2017 7th International Conference on Power Systems (ICPS), Pune, India, 2017, pp. 410-415.
- [3] S. N. Soheli, U. S. Aney and S. I. Mahmud, "Designing A Highly Effective DC-DC Buck Converter for Sustainable Electronic Applications," 2021 2nd International Conference on Robotics, Electrical and Signal Processing Techniques (ICREST), DHAKA, Bangladesh, 2021, pp. 178-182.
- [4] C. Keerthika, S. Ramprasath, P. Rameshbabu and C. Krishnakumar, "Simulation and Steady State Analysis of SIMO Boost Converter for Electric Vehicles," 2021 2nd International Conference for Emerging Technology (INCET), Belagavi, India, 2021, pp. 1-5.
- [5] M. Ramesh, B. Mallikarjuna and T. Rajasekar, "A Novel Investigation on Single-Input Three-Output DC-DC Buck Converter For Electrical Vehicles," 2021 7th International Conference on Electrical Energy Systems (ICEES), Chennai, India, 2021, pp. 141-146.
- [6] M. R. Haque, K. M. A. Salam and M. A. Razzak, "A High Gain Cascaded DC-DC Boost Converter for Electric Vehicle Motor Controller and Other Renewable Energy Applications," 2022 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS), Toronto, ON, Canada, 2022, pp. 1-5.
- [7] H. Qiao, Y. Zhang, Y. Yao and L. Wei, "Analysis of Buck-Boost Converters for Fuel Cell Electric Vehicles," 2006 IEEE International Conference on Vehicular Electronics and Safety, Shanghai, China, 2006, pp. 109-113.
- [8] M. S. Khan, S. S. Nag, A. Das and C. Yoon, "A Novel Buck-Boost Type DC-DC Converter Topology for Electric Vehicle Applications," 2021 IEEE Energy Conversion Congress and Exposition (ECCE), Vancouver, BC, Canada, 2021, pp. 1534-1539.
- [9] S. Rathod and M. S. Aspalli, "Design and Analysis of SEPIC Converter for EV Battery Charging Applications with IoT Based Monitoring System," 2022 IEEE 2nd Mysore Sub Section International Conference (MysuruCon), Mysuru, India, 2022, pp. 1-7.
- [10] A. M. Khatab, M. I. Marei and H. M. Elhelw, "An Electric Vehicle Battery Charger Based on Zeta Converter Fed from a PV Array," 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Palermo, Italy, 2018, pp. 1-5.
- [11] H. L. Puvendran and N. Narmadhai, "A Compact Integrated Converter for Plug-In Electric Vehicles," 2022 1st International Conference on Sustainable Technology for Power and Energy Systems (STPES), SRINAGAR, India, 2022, pp. 1-6.
- [12] N. K. Meena, R. Kumar, K. Shukla and A. Haque, "Integration of High Gain Re-Lift Luo Converter with Buck Converter for Electric Vehicle Application," 2022 Second International Conference on Power, Control and Computing Technologies (ICPC2T), Raipur, India, 2022, pp. 1-6.
- [13] A. M. Omara and M. Sleptsov, "Bidirectional interleaved DC/DC converter for electric vehicle application," 2016 11th International Forum on Strategic Technology (IFOST), Novosibirsk, Russia, 2016, pp. 100-104.
- [14] S. Taghizadeh, M. J. Hossain and J. Lu, "Efficacy of Interleaved Two-leg Buck-boost Converter in EV Charger Design," 2018 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), Amalfi, Italy, 2018, pp. 601-606.