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Review Article

A Complete Review on DC-to-DC Converter Topologies for Energy Sustainable Electro-mobility under Environmentally Heterogeneous Power Conditions

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ABSTRACT

The electric vehicle is an upcoming technology that upgrades the biosphere and diminishes pollution across the globe. Electric Vehicles powered by batteries mitigate the problem of the emission of greenhouse gases and air pollution. Research has been undertaken lately to integrate sources of renewable energy to electrify the E-Vehicle to reduce the dependency on fossil fuels, making it an eco-friendly and nil carbon emission transport system. The increased usage and the forecasted growth of E- -vehicles urge the research to be centered on power electronic converters to attain highly efficient, cost-effective, and reliable charging infrastructure for the vehicle battery. The pivot necessity is to provide electricity to the E-vehicle efficiently and continuously. Apart from battery and grid voltage levels, electric vehicles have several systems operating at a variety of power levels. This makes the role of DC/DC converters inevitable in EV operation. This paper presents various DC/DC converter topologies that are employed in EV charging and power conversion techniques. Basic topology and working are first described along with recent developments and variants of basic topologies are also presented.

Index terms: Electric vehicles; Nanotechnology; Power electronics; DC/DC converters.

1. INTRODUCTION

With the steep rise in the production of greenhouse gases and scaling down of non-renewable energy sources, the search for alternative sources, most probably clean or green energy become inevitable over the last decade. Energy is the core of every industry and is essential for the growth of every economy. Road transportation accounts for a major share in the release of greenhouse gases, making it a main cause of air pollution. Various research has been undertaken on fuel cells and hydrogen-based energy sources and sustainable energies (e.g. solar, wind, Geothermal, etc.) and making electricity from these sources which eventually minimizes the influences of non-renewable sources. Eventually this results in the rise of Electric vehicles. Electric vehicles are considered more efficient than fossil fuel-based vehicles since they produce pollution-free energy. But again, making non-renewable sources a contributor of power does not change anything. It becomes mandatory to produce electricity from green energy like solar and wind. Solar panels are gaining momentum which makes the manufacturing of efficient photovoltaics mandatory. When we investigate the greenhouse emissions in India, it has doubled since the turn of the century with an ongoing value of 4 billion metric tons of Co_2 equivalent ($GtCo_2e$) per year. During this time, India's Co_2 emission levels have increased thrice and reached a new high value of 2.7 $GtCo_2e$ in 2022. It is increasing alarmingly worldwide leading to worldwide research in electric vehicles and renewable energy sources.

In this work, we examine how surface roughness and machining time during Inconel 625 machining are affected by Novel Al-Ni electrodes. We seek to decipher the complex interactions between electrode composition, machining settings, and surface quality by using a thorough performance analysis. In the context of Inconel 625 machining, we get important insights that help optimize machining operations for increased efficiency and surface polish through methodical testing and data analysis. One non-traditional machining method is the electric discharge machine (EDM). It finds several uses in the die-making, punching, and mold-making industries. It is also used in the production of surgical components as well as whole automotive parts. Che Haron *et al.* (2001) investigated the influence of machining parameters of steel, where the work piece and tool electrode are both submerged in a dielectric fluid, such as kerosene or EDM oil. The spark gap is the distance between the electrode and work piece, which varies according on the operating circumstances.

Fig. 1 clarifies that the freight business, particularly the automotive sector, is the main source of carbon emissions. This makes the shift to clean energy mandatory. Shoot-ups in EV sales happen due to the government's efforts by giving subsidies and other measures like waiving the toll fares (Jovanović *et al.* 2023). Other factors influence the steep rise in EV usage like consumers' environmental concerns (Farajnezhad *et al.* 2024). Escalation in EV acceptance poses major problems like overloaded transformers and grid and power quality problems. Most of these problems are directly connected to the charging methods and the charger of EVs. There comes the role of power electronics. It is used to charge the battery and run any drive (Afonso *et al.* 2020). The main expected output of an EV is high efficiency and extended driving range. Various attempts and advanced techniques are continuously researched to mitigate the problem of driving range and battery recycling.

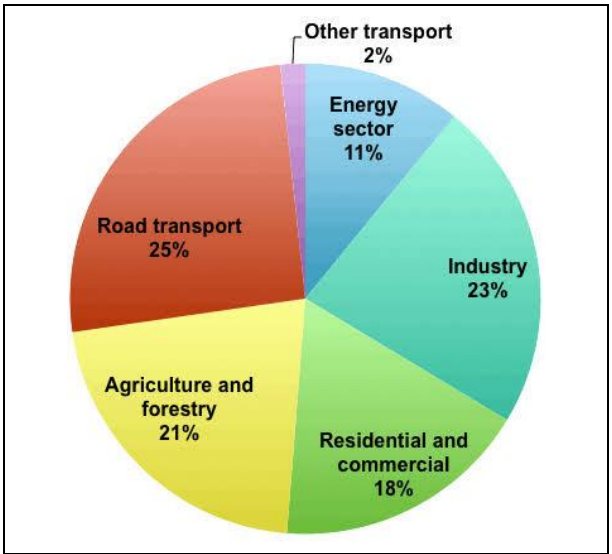

Fig. 1: Greenhouse Gases Emissions by Industry

Nanotechnology has extended a helping hand in improving the manufacturing of batteries and their efficiency (Shafique *et al.* 2019; Kumar *et al.* 2024). Also, to decrease the CO_2 emission and carbon footprint, effective handling of auxiliary items added to the cement is presented (Singh *et al.* 2020d). The charging process and the charger need thorough investigation and continuous improvement. In addition to this, the charging time is also high. The means of fast charging methods are also under investigation and research (Suarez *et al.* 2019). Perhaps such categories take advantage of DC power to recharge which imposes a separate charger off the vehicle for recharging the battery. Also, the ranges of most EVs are lower than their gasoline counterpart. There is a need for the improvement of the charger and charging process.

Power electronics is a crucial component in the charging infrastructure of the EV, especially power electronic converters. The converters might be AC / DC, DC/DC, or DC/AC converters. Here the AC-DC converters take the front end connecting the EV with the grid and taking care of the PFC part. The DC-DC conversion controls the charging part of the EV battery and connects the battery with the DC link bus and other low-voltage auxiliary systems within the vehicle. The DC-AC stage connects the battery with the electric drive if it is AC.

As we have already discussed how recharging the battery is vital for an EV's performance and range, DC/DC converters are a critical part of an EV charger. Detailed discussion on the categorization of DC-to-DC converters is conferred here. The DC-to-DC converter is a power electronic assembly comprising power electronic switches, diodes, inductors, and capacitors which either escalates or cuts off the voltage. The DC/DC converters can be classified based on various criteria like structure, direction of power flow, galvanic seclusion, etc. Depending on the direction of power flow, they are subdivided into Unidirectional and Bidirectional converters. In Unidirectional converters, the power flows in one direction (Bist *et al.* 2014), and in Bidirectional converters, the power flow is in two directions (Lee *et al.* 2009). The bidirectional converters offer multi-functionality like V2G, V2H, etc. (Jahnes *et al.* 2023). The performance analysis of such converters is presented in (Ahmed *et al.* 2013).

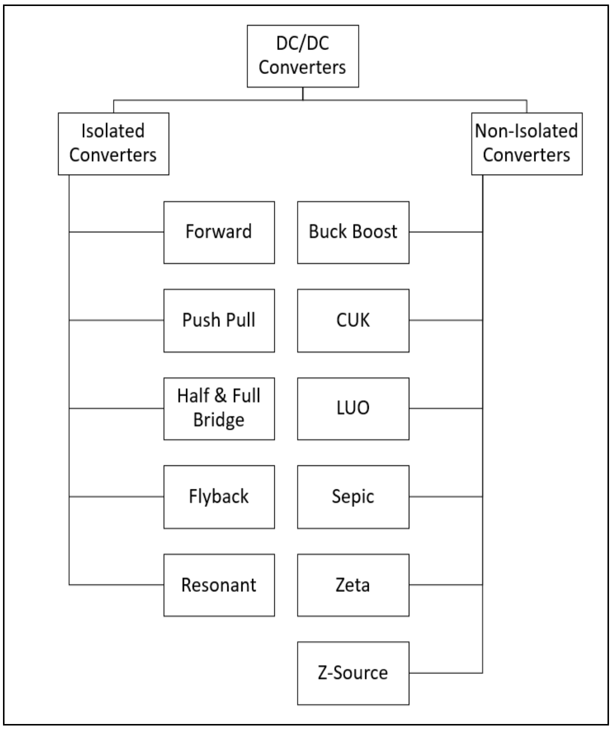

Fig. 2: DC/DC converters types

As illustrated in Fig. 2, the DC-to-DC converters are split up into isolated and Non-Isolated converters based on the component configuration. In Isolated converters, there is electrical and physical separation between the source and the load side (Ma *et al.* 2017; Singh *et al.* 2020a). In non-isolated converters, there is no separation between the source and the load side (Athikkal *et al.* 2019; Banaei *et al.* 2020). Isolated converters are utilized for small and average power demands, the isolated type is used whereas, for large power demands, the Non-Isolated type is utilized (Alassi *et al.* 2017). Every DC/DC converter can be categorized under three basic categories as follows

- Buck
- Boost
- Buck Boost

All the other converters are derived from one of these converters.

2. BUCK CONVERTER

A Buck Converter is a DC/DC converter where the output value is always less than the input value. It consists of an active switch, a MOSFET or IGBT, an inductor, a diode, and an output capacitor. In this case, the voltage is regulated by manipulating the frequency of the switch and is given as

$$Vo = Vin\ D$$

where, D implies the duty ratio of the MOSFET or IGBT.

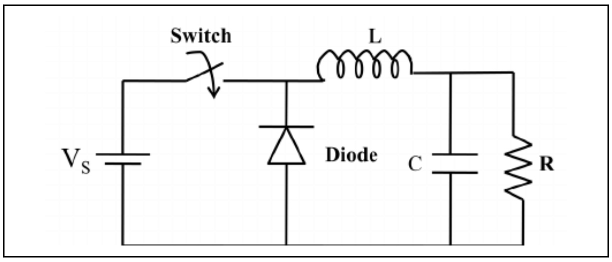

Fig. 3: Buck Converter

At the moment of switch closing, the source and the inductor get coupled and it stocks energy. When the switch is open, the source is disconnected and the energy gathered in the inductor is passed on to the output. There is always a loss in the inductor. So, the outputted voltage is always lesser than the inputted voltage. The major application of this type is in personal computers to match the main high voltage supply with the low voltage devices like USB, Random Access Memory, etc. (less voltage).

2.1 Boost Converter

A DC-to-DC converter with a bigger output than input is called a boost or step-up converter. The structure or components of a Boost converter are nearly equal to the Buck type but the position of the switch and the inductor changes. In the Buck converter, the Inductor is on the load part but in the Boost converter, it is on the input side. The formula for output voltage here is

$$V_o = V_{in}/(1\text{-}D)\ r$$

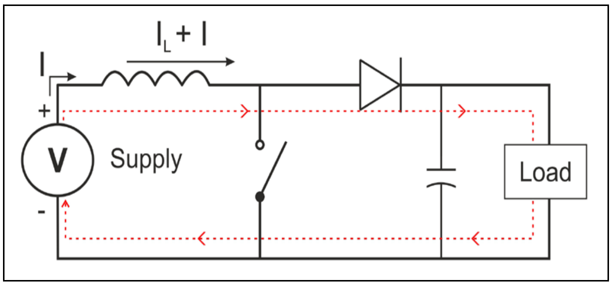

Fig. 4: Boost Converter

At the moment of switch closing, energy stocking happens in the inductor and at the time of opening of the switch, both the input voltage and the stocked voltage are delivered to the load, hence the level of load voltage is always elevated than the level of voltage at the input. In electric vehicles, to scale down the dimensions of the battery and the number of cells to be stalked, Boost regulators are exploited. These are also utilized in LED lighting systems where it increases the voltage of one alkaline battery to light white LED which usually requires two batteries.

2.2 Buck – Boost

It belongs to the third category of DC-to-DC converter where the level of the load voltage is usually lower or higher than the level of input. That is the output can be increased or decreased using a Buck-Boost regulator. The components list is the same as that of the Buck and Boost kind, but the position of the switch and the inductor varies. In correspondence with the duty ratio, it is possible to adjust the output voltage above or below the input voltage.

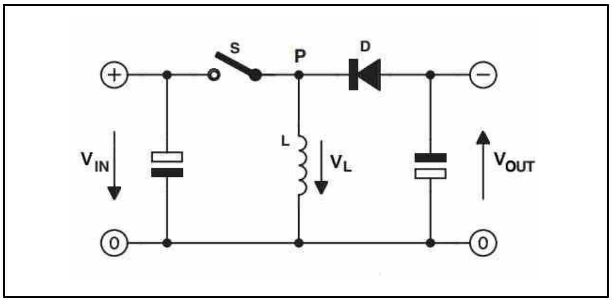

Fig. 5: Buck-Boost converter

The formula for voltage output is

$$V_o = -V_{in}.D/1\text{-}D$$

where, D - duty ratio of the active switch. For duty ratio values elevated above 0.5, a larger output is sensed. D>0.5, Vo>Vin. For duty ratio values reduced below 0.5, a smaller output is sensed. D<0.5, Vo<Vin. In relation to the input, the controlled output is polarity opposite. The converter has a low cost and minimal component count. But no seclusion exists between the input and the output. A busk-boost-based battery charging method is presented in (Nayak *et al.* 2021). The buck-boost regulator used as a PFC circuit for plug-in electric vehicles is presented in

(Mehta *et al.* 2016) Buck-Boost converter is a unidirectional converter i.e. it allows power to flow from the source to load only. A Buck-Boost converter with less component stress is sketched in (Chen *et al.* 2006) for power factor correction uses.

2.3 Cuk Converter

The Cuk converter is a member of the buck-boost DC-to-DC converter family, which produces outputs that are either greater or less than their inputs. It combines buck and boost technology and is connected via a capacitor. The formula for calculating the output voltage of a CUK converter is

$$V_o = V_{in}(-D/1-D)$$

At the load, an inverted output is generated. The CUK converter exhibits lower output ripple compared to the buck-boost due to its continuous load current-driven inductor at the load side. The advantages of the Cuk converter include continuous source and load currents, extended range of input voltages, and low electromagnetic interference. Cuk converters are extensively employed in renewable energy implementations where high efficiency is required. An amplified load power quality is attained using a switched inductor type Cuk converter which is specially needed for charging EV batteries (Ananthapadmanabha *et al.* 2018) This converter is capable of supplying regulated output despite grid and load variations.

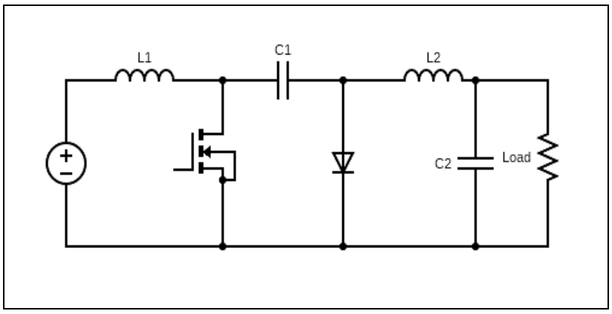

Fig. 6: Cuk Converter

2.4 Luo Converter

The Luo converter belongs to the family of step-up DC-to-DC converters where the level of load voltage is at a greater level concerning the source level. This converter uses a voltage lift technique to surge the output voltage. The formula of the regulated output is

$$V_o = V_{in}(D/1-D)$$

The polarity of the load voltage can be of identical polarity or of opposite polarity of that of source voltage. It is dependent on the position of the diode and the capacitor. This topology is simple and cheap has more power density and is highly efficient. They can produce output voltage with low output ripples. The output voltages can be produced in geometric progression. They are commonly used in computer system peripheral components. Four Luo topologies are discussed and compared in 2014. An EV charger based on an altered Luo regulator is discussed in (Kushwaha *et al.* 2019) with improved power quality for EV battery charger applications.

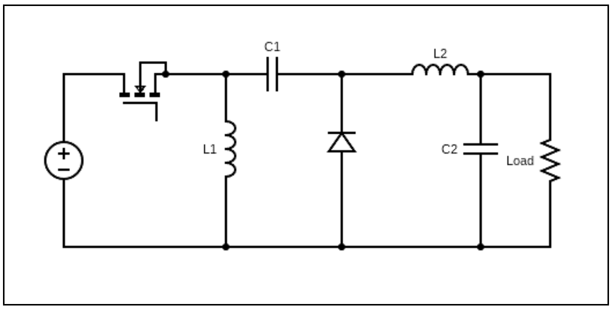

Fig.7: Luo converter

2.5 SEPIC Converter

SEPIC converter belongs to the pack of Buck-Boost type of DC-to-DC converter where the output is either lesser or greater than the input. It is a boost converter cascaded with a reversed buck converter. So, it is identical to the Buck-boost operation with an additional merit of output with the same polarity as input. The regulated output of the SEPIC converter is

$$V_o = V_{in}(D/1-D)$$

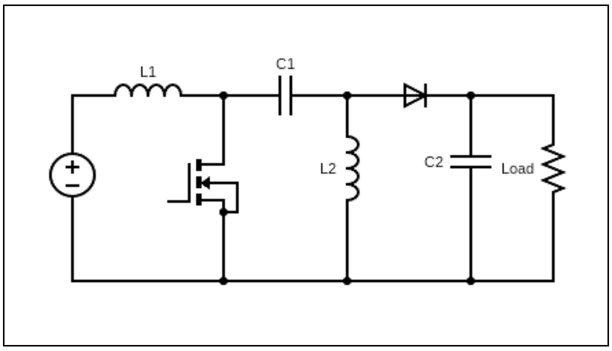

Fig. 8: SEPIC converter

The SEPIC converter employs a capacitor to link the source side with the load side. It can be operated in continuous or discontinuous conduction modes. The Buck/boost operation of SEPIC is possible due to the inductor L_2 and capacitor C_1. Switch S_1 and inductor L_1 creates the boost part of the converter whereas the voltage across the switch S_1 decides whether it acts as a boost or buck converter. If the voltage of the active switch is lesser than double Vin, then the output is lower than the input and if it is higher, the voltage at the output will be elevated than the voltage level at the input. The output current is oscillating and it needs a capacitor with a large capacitance value. The SEPIC converter is used for correcting the power factor and PV applications, in which constant fluctuations in the voltage level happen at the input side. A power factor-corrected EV charger employing a Sepic converter is discussed in (Singh *et al.* 2020c). The basic topology is non-isolated but a modified isolated topology-based integrated charger is presented in (Singh *et al.* 2020a). A Sepic-based PFC rectifier is proposed in (Mahdavi *et al.* 2011) with reduced components and less conduction losses.

2.6 ZETA Converter

It is a DC-to-DC converter that either steps up or steps down the input and belongs to the group of Buck-boost converters. It can be considered as a modification of the CUK converter as they share similar characteristics. The output is of the same polarity and is given as

$$V_o = V_{in}(D/1-D)$$

The structure is similar to that of a SEPIC converter and it is also called an inverted SEPIC because unlike SEPIC which is derived from a step-up converter, zeta is derived from a step-down converter.

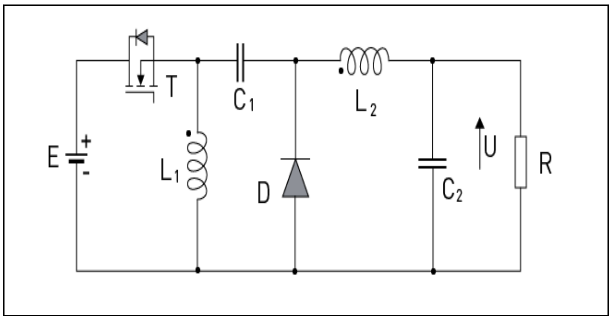

Fig. 9: Zeta converter

The Zeta converter is capable of managing persistent output. Low input and output current ripples are the main advantages of the zeta converter. It has the additional advantage of short-circuit protection. ZETA converter has high efficiency, especially for photovoltaic systems when compared to Cuk and SEPIC topologies (Boonraksa *et al.* 2021). ZETA converter is also used for PFC because it has continuous input and output current. A zeta converter-based PFC circuit for SMPS with enhanced quality of power is achieved (Singh *et al.* 2015b). The results show that the circuit achieves almost unity power factor for an extended range of input voltages and loads. Zeta converter is widely used in battery charging in EV applications since it has less output current ripples.

2.6.1 Z – Source Converters

Z-source converters are state-of-the-art DC-to-DC converters that can either shoot or cut the input voltage with respect to the duty ratio of the active switches. They can offer a wide range of output voltages with minimal in-rush and ripple currents. In comparison with other converters, these have fewer noise ripples, lower duty cycle, and compact size.

The basic topologies of Z-source converters are discussed in (Lin *et al.* 2016). A state-of-the-art Z-source DC-to-DC converter is presented and simulated in (Fang *et al.* 2008). The source can be of current or voltage origin. The cost of the proposed converter is also less and with improved reliability. A Non-Isolated Z-source DC/DC converter especially for boosting the voltage in photovoltaic usages is discussed in (Torkan *et al.* 2018). This converter has increased gain and reduced stress when compared to the regular one. It is experimentally used to change 24V to 300V at 100 W.

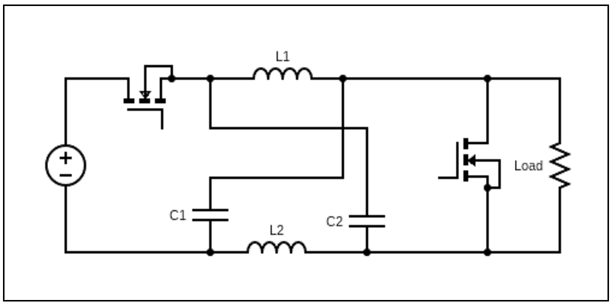

Fig. 10: Z-source converter

2.6.2 Isolated DC/DC converters:

In Isolated DC/DC converters, seclusion occurs between the source and the load side that is there is a physical separation. This can be realized by the use of a transformer in between the two sides and this results in no direct current flow among the two. An additional advantage is that with multiple output windings on the load side, we can get multiple output voltages.

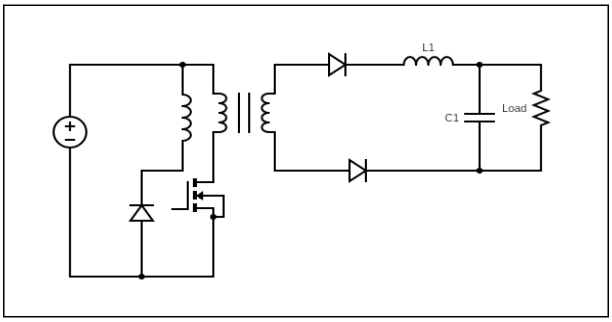

Fig. 11: Forward converter

2.7 Forward Converter

A forward converter is a member of the Buck-Boost family and an isolated DC/DC converter. It is a unidirectional converter that the power transfers only from source to load, only in the forward direction as the name implies. The output voltage of the forward converter is calculated as

$$V_o = nV_{in}D$$

Where 'n' is the turns ratio of the transformer. 'D' is the duty cycle of the active switch.

F If 'n' is higher than 1, then the transformer is a step-up one producing a boost output and if the turns ratio 'n' is lower than 1, the transformer is a step-down one producing a reduced output performing a buck operation. The power transfer from source to load occurs due to transformer action and there is no energy storage here in this converter. The forward converter is mainly used for high-current applications and is not suited for high-voltage applications. A forward converter with two transformers with active clamp and erratic conversion ratio is proposed in (Lin *et al.* 2016). This converter has parallel output and magnetizing reset with only two active switches.

2.8 Push-Pull Converters

Push-pull converter is an isolated DC-to-DC converter that utilizes an isolation transformer to do the power transfer from input to output but it has two windings and two active switches on the primary and two windings on the secondary with a center tap on both sides. The active switches are alternatively ON and OFF periodically changing the current in the transformer hence the name Push-Pull converter. Here output is computed as

$$V_o = nV_{in}D$$

In this type, the power Transfer happens for a full duty cycle contrary to one-half in the remaining converters. A Push-Pull converter has high efficiency and low conduction losses. It has regulated grid current and little noise on the input line and well-suited for high power applications. A push-pull converter with a vast range of step-up power conversion ratios is proposed in (Wang *et al.* 2021). This converter can handle an extensive range of input voltages of high value and has been experimentally tested for unregulated low input voltage to high voltage load. A suggested battery charger for e-vehicles specifically uses a push-pull converter. To correct for power factor and regulate power to the battery, this study suggests a two-stage power supply method.

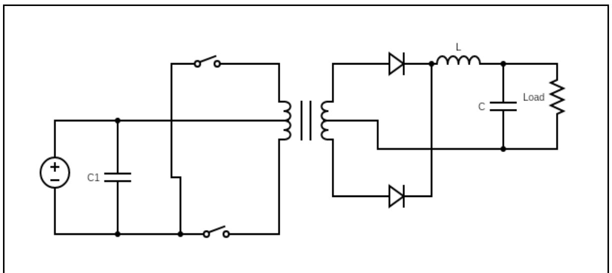

Fig. 12: Push-Pull Converter

2.9 Half-bridge and Full-bridge Converters

As the name implies both the Half-bridge and full-bridge converters are composed of active switches in bridge form to perform buck or boost operation. It is a member of the isolated type of converter where the primary of the transformer is connected to the bridge.

The Full-bridge converter consists of two legs of a Half-bridge converter. The formula for calculating the half-bridge converter output is

$$V_o = nV_{in}D.$$

The formula for the full-bridge converter output is

$$V_o = 2nV_{in}D.$$

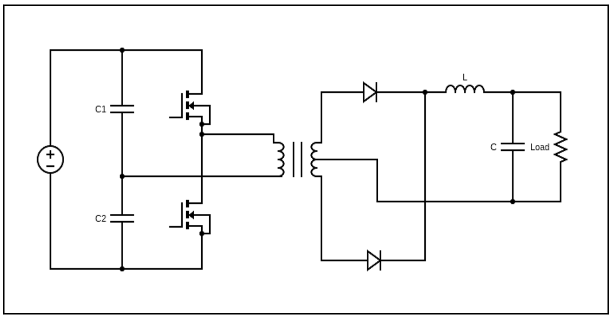

Fig. 13: Half-bridge converter

Because of its superior efficiency over half-bridge converters, full-bridge converters are used in high-power operations. This is because they minimize losses and employ ZVS or ZCS approaches. The output level of the full bridge is double the Half-bridge. They are widely used in applications employing sustainable energy and telecommunication sectors. A one-stage isolated converter based on half and full-bridge converter for DC/AC applications is proposed in 2021. A half /Full bridge converter-based bidirectional EV charger is proposed in (Koushki *et al.* 2023).

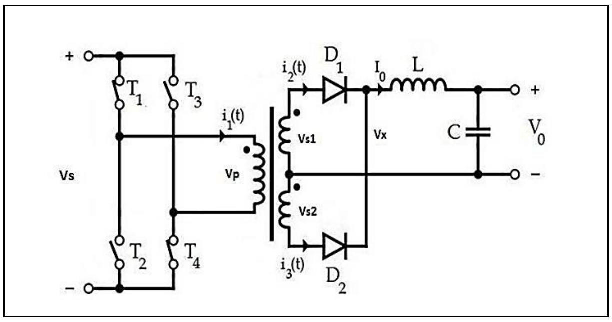

Fig. 14: Full-bridge Converter

2.10 Flyback Converter

Flyback converter is the simplest of the isolated type converters and hence it is the most popular as a commercial one. This circuit has only one active switch which controls the flow of power within the windings of the isolation transformer. Even when the transformer is used, it acts as two inductors that store the energy in the airgap that is the inductor is split to form a transformer. It is a buck-boost type of converter. Its main advantages are simple architecture and low cost. This also belongs to Buck-boost type of converters. The output is computed by

$$V_o = V_{in}(nD/1\text{-}D)$$

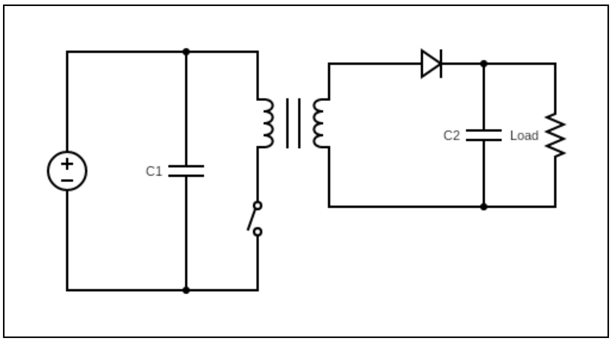

Fig. 15: Flyback converter

They are employed in medium and low-power applications. This type is widely used in Television sets, standby power supplies for computers, cellphones, mobile device chargers, and medical devices. A high-efficiency flyback converter topology is proposed in (U.Bocke). An active clamped bidirectional flyback converter is advised but it has the disadvantage of having high voltage device stress on the components.

2.11 Resonant Converter

The resonant converter uses a resonant tank circuit comprising of inductor and capacitors which resonate at a certain frequency depending on the value of the inductor and the capacitor. They will work at high switching frequency and reduce switching losses. These are often engaged in high switching frequency and high-power applications. Resonant converters have four blocks namely active switches, transformer, tank circuit, and the bridge rectifier.

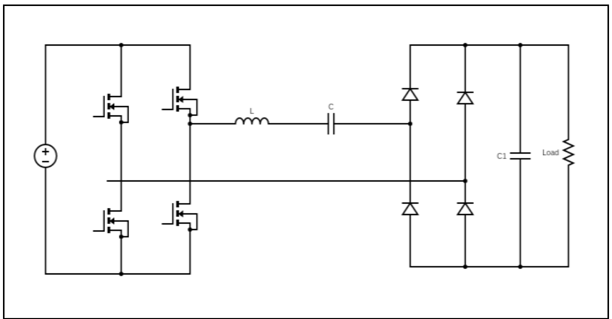

Fig. 16: Resonant converter

The resonant circuit transfers DC to AC first, then steps up or down, and then converts back to DC. The regulated output is calculated using the formula

$$V_o = V_{in}\, n(j2\pi f)$$

Soft switching is enabled in this type; hence it reduces the losses due to switching and improves the efficiency. An LLC DC-to-DC converter with high efficiency for EV applications with high power density is proposed in (Zhou *et al.* 2021). In this topology, switches can achieve ZVS ON and OFF. A two-way DC/DC resonant converter for V2G applications is proposed in (Zahid *et al.* 2015). This is an LLC form of resonant converter with another capacitor and inductor on the secondary side. Soft switching is used for all the switches so high frequency operation is possible.

2.12 Recent Developments

Everything in this world needs continuous improvement and undergoes constant changes depending on the time and need. The topologies discussed above are basic topologies and have been widely used in various power electronic implementations depending on the requirement. Numerous amendments and advancements have been exercised to these structures to obtain the needed traits. The interleaving technique is used to achieve a high-power level, ample capacity, minimal ripples on the load current, and high efficiency during light loads. A battery charger for EV implementations employing an interleaved Zeta converter has been proposed (Singh *et al.* 2015a). Usually, the bridge rectifiers impose harmonics problem so here it is eliminated using the interleaving technique.

Multi-input, multi-output converters have been developed for hybridizing energy sources like Grid input with solar PV, fuel cells, or supercapacitors and giving outputs at different voltage levels for battery and other auxiliary systems in EVs. For EV applications with hybrid energy integration, a multiple input two directional DC/DC converter has been proposed by F. Akbar. A dual output converter for plug-in electric vehicles is proposed by (Tang *et al.* 2018). The converter may accomplish V2G operation, or bidirectional power flow, in addition to integrating the HV and LV batteries with the grid. There are also integrated converters in which the same converter performs more operations like power factor correction, grid-to-vehicle power transfer [G2V], vehicle-to-grid power transfer [V2G], Regenerative braking, etc. Such a multi-functional converter in an On-board charger for EV application has been proposed by (Singh *et al.* 2020b). These converters generally employ bi-stage operation but one-stage action with few additional parts is also developed.

3. CONCLUSION

Electric vehicles are energy-sustainable transport systems environmentally that have been gaining momentum in recent decades for the formation of eco-friendly and clean energy systems. The EV sector needs continuous rectifications and improvements to increase the driving range and reduce the cost when compared to ICE-based vehicles. As Power electronic converters play a vital role in EV systems, this review paper presents various basic DC/DC power converter topologies, their basic working principle, and types. The characteristics of these converters are discussed and their usage in electric vehicle-based applications has been presented in several research articles. Their advantages and disadvantages and similarities and differences have been discussed. Recent developments in these converters with their applications are also presented.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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