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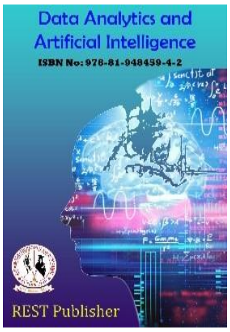


Contemporary Trends in Power Electronics Converters for charging solutions of Electric Vehicles

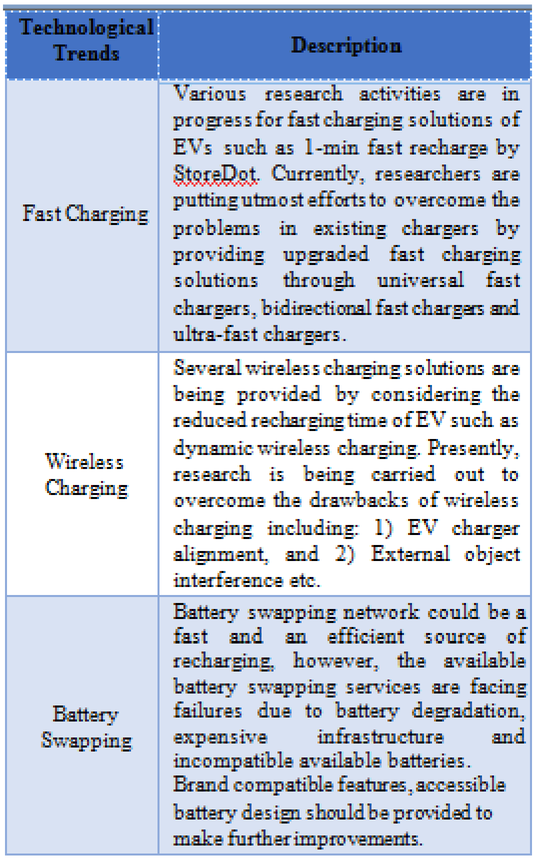
A. Asha, D. Aruldevi, R. Gayathri
PSN Institute of Technology and Science, Melathidiyoor, Tirunelveli, Tamil Nadu, India

Abstract. *Electrifying the transport sector requires new possibilities for power electronics converters to attain reliable and efficient charging solutions for electric vehicles (EVs). With the continuous development in power electronics converters, the desire to reduce gasoline consumption and to increase the battery capacity for more electric range is achievable for EVs in the near future.The main interface between the power network and EV battery system is a power electronics converter, therefore, there is a considerable need of new power converters with low cost and high reliability for the advance charging mechanism of EVs. The rapid growth in power converter topologies brings substantial opportunities in EV charging process.*

Keywords: *Batteries chargers, Converter topologies, Electric vehicles (EVs), Power electronics, Plug-in hybrid electric vehicles (PHEVs)*

1. INTRODUCTION

In the last decade, worldwide challenging concerns including the global call for clean energy,imminent energy crises, depletion of conventional resources and fossil fuel dependence are driving the demand to adopt the new eco-friendly technologies. Transport and power sectors are directly linked with all the considerable climate and environmental issues as contributing largely in utilizing fossil fuels and CO_2 emissions. The emission rate can be considerably reduced by electrifying the transport sector with smart grid involvement. Recently, EVs as an eco-friendly power source are gaining much popularity with a promising objective to replace internal combustion engines (ICEs) and to reduce CO_2 emissions. Worldwide, the government and researchers are working collaboratively to lessen fossil fuel dependence with clean energy solutions. The development and deployment of EVs are rapidly observed with new incentive-based policies introduced by the government and policy-makers [1],[2]. The incentive policies formulated by the government are based on financial measures, which include tax exemption (vehicle purchase tax), exemption from road tolling and preferred parking place for extensive consumer adoption. The rapid demand of EVs in the transportation sector is the result of growing alarms about clean energy and environmental problems. Regular increments in fuel prices and high standard environmental policies are driving the need for an energy system, which has a much higher contribution of EVs. In the transportation sector, the EVs act as an emerging approach and an alternative technology, which can alleviate the non-renewable fossil fuel dependency [5]? Lower operating costs, better fuel economy with reduced carbon emissions are the reasons for higher preferences of EVs [6],[7]. The participation of EVs in a smart grid environment offers many substantial features including load balancing, peak load shaving, revenue generation and tracking of renewable energy resources (RES) are observed [8],[9],[10]. Advancements in EV charging technology based on converter topologies contribute towards many significant benefits of EVs over many other traditional clean energy applications.



Technological Trends	Description
Fast Charging	Various research activities are in progress for fast charging solutions of EVs such as 1-min fast recharge by StoreDot. Currently, researchers are putting utmost efforts to overcome the problems in existing chargers by providing upgraded fast charging solutions through universal fast chargers, bidirectional fast chargers and ultra-fast chargers.
Wireless Charging	Several wireless charging solutions are being provided by considering the reduced recharging time of EV such as dynamic wireless charging. Presently, research is being carried out to overcome the drawbacks of wireless charging including: 1) EV charger alignment, and 2) External object interference etc.
Battery Swapping	Battery swapping network could be a fast and an efficient source of recharging, however, the available battery swapping services are facing failures due to battery degradation, expensive infrastructure and incompatible available batteries. Brand compatible features, accessible battery design should be provided to make further improvements.

Recent research revealed that EVs can be integrated with many RES including wind, solar panels, fuel cells, etc. to realize the improved performance of power networks [8],[10]. The current technological trends in EV charging technology are presented in Table I [11],[12],[13]. New opportunities and applications are introduced by National Renewable Energy Laboratory in terms of advanced simulation tools to make optimal charging strategies and further advancement in EV charging technology [14]. International standards for utility interface are developed by many reputed organizations such as IWC (Infrastructure Working Council), SAE (Society of Automotive Engineers) and Institute of Electrical and Electronics Engineers (IEEE). Despite several developments in EV technology, there are still some potential barriers including charging infrastructure, a suitable design of battery chargers (converter topologies), battery degradation and driving range issues for widespread adoption [15]. Harmful harmonics are introduced by EV chargers, which lead to potential issues for distribution networks in terms of its stability and power quality. Harmonic compensation techniques and improved converter topologies are employed to reduce power quality issues [16], [17]. As far as charging power levels are concerned, Level 1 charging is employed at residential levels. Higher charging levels (Level 2 and Level 3) are required at commercial locations including shopping malls, rest areas and various parking lots. Comparative analysis of various AC and DC charging power levels as explained by several international standards [18],[19],[20] is summarized in Table II.Electrifying the transport sector requires new possibilities for power electronics converters to attain reliable and efficient charging solutions of EVs. With the continuous development in power electronics converters, the desire to reduce gasoline consumption and to increase the battery capacity for more electric range, is achievable for EVs in the near future [21]. The main interface between the power network and EV battery system is a power electronics converter, therefore, there is a considerable need of new power converters with low cost and high reliability for advance charging mechanism of EVTechnological Trends Description Fast Charging Various research activities are in progress for fast charging solutions of EVs such as 1-min fast recharge by StoreDot. Currently, researchers are putting utmost efforts to overcome the problems in existing chargers by providing upgraded fast charging solutions through universal fast chargers, bidirectional fast chargers and ultra-fast chargers. Wireless Charging Several wireless charging solutions are being provided by considering the reduced recharging time of EV such as dynamic wireless charging. Presently, research is being carried out to overcome the drawbacks of wireless charging including: 1) EV charger alignment, and 2) External object interference etc. Battery Swapping Battery swapping network could be a fast and an efficient source of recharging, however, the available battery swapping services are facing failures due to battery degradation, expensive infrastructure and incompatible available batteries. Brand compatible features, accessible battery design should be provided to make further improvements.

2. CONVERTER TOPOLOGIES FOR EV BATTERY CHARGERS

Improved converter topologies of a battery charger have a substantial role in the further development process of charging infrastructure of EVs. The standard properties of a battery charger reflect the battery life degradation and required charging time. EV design challenges are introduced by various types of battery chargers as being the main power source. Driving range of EV is significantly dependent on design constraints of battery chargers including weight, volume and power density. Several switching techniques with control connections are involved in proper working of a battery charger. However, the hardware configurations related to battery charging decide the required control algorithm and type of switching methodology. Various control algorithm needed for charging can be implemented with the help of converters, integrated circuits, microcontrollers and signal processors

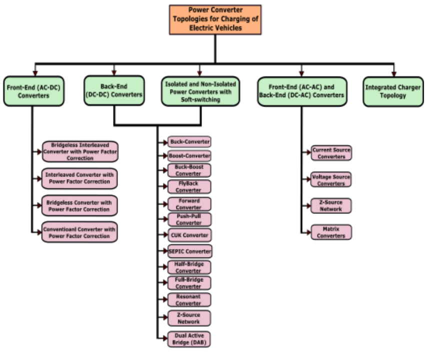


Figure 1: Power Electronic Converters for Charging Solution of EVs

FIGURE 1

In EV charging market, sales up-to 23.13million units are projected for AC chargers by 2020 with a compound annual growth rate (CAGR) of 27.29%, consequently, highlighting the dominance of AC chargers. Wireless chargers are in emerging phase with a 3% contribution in the EV market. Large-scale deployment of EVs contributes towards a bigger market of battery chargers. Globally, the key market leaders in AC/DC EV battery charger industry are: 1) ABB, 2) Siemens, 3) Evatran, 4) Leviton, 5) Plugin Now, 6) Addnergie, 7) AeroVironment, 8) POD Point, and 9) Delphi Automotive. In case for wireless chargers, the major companies are: 1) Duracell Powermat, 2) Fulton Innovation, 3) Qualcomm and WiTricity, and 4) Texas Instruments

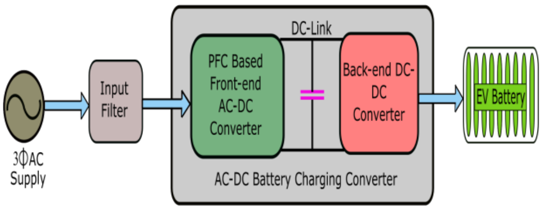


Figure 2: EV Power Architecture of a Battery Charger

FIGURE 2

A bidirectional EV converter topology based on dual active bridge is proposed in [55] for providing the control of power flow in low voltage networks. The proposed control scheme allows large-scale penetrations for EVs and renewable resources in power networks. The control of power flow and power factor correction is achieved with the full-bridge grid-tied inverter and battery current regulation is obtained with the isolated dual active bridge. The proposed control architecture of EV charger with capability of bidirectional power is presented in fig.4(d). The architecture of power converter is divided into two stages and each stage has its own control strategies. The first stage is for power control and second stage performs current regulation. The grid voltage along with voltage of DC bus and current variables are measured by the control scheme of full-bridge inverter. The phase and frequency of grid voltage is measured by the PLL algorithm. Moreover, active and reactive powers are further computed to realize the PQ control. PI controller is used to perform the error compensation and anti-windup feature is used to certify the high standards of power quality. Further details of control architecture are provided in [55]. The study concluded that if the concept of frequency-voltage droop is implemented for the control of power flow, various power quality benefits can be obtained for micro girds. This demands the use of Schottky and Silicon Carbide (SiC) diodes. This need will make a potential rise in the overall cost of the converter. Bridgeless boost converters including symmetrical and asymmetrical configurations show an improved version then the conventional converter in terms of higher efficiency and heat issue as conducting devices are reduced; however, higher reverse recovery loss of an output diode and increased EMI still makes the limitation [56],[57]. Other challenging issues are the compulsory use of a low frequency transformer to sense the input voltage and control circuitry for the detection of an input current in the power switches. A battery charger having high efficiency is proposed in [48] based on space vector pulse width modulation at front-end stage and full-bridge converter at back-end stage for charging of EVs. For this two-stage topology, dc-link is required to deliver decoupling between the stages. Independent control regarding active as well as reactive powers is achieved by implementing a decoupling method. To regulate the active and reactive power, PI controllers are utilized. Better dynamic performance is obtained with the proposed strategy. Experimental results are included for the complete process of EV charging. The input power factor is closed to unity and efficiency is higher than 85%. Various front-end converters are comparatively described with their constraint analysis in study [53] to show their suitability for the support of reactive power in vehicle to grid operation. A bidirectional EV converter topology based on dual active bridge is proposed in [55] for providing the control of power flow in low voltage networks. The proposed control scheme allows large-scale penetrations for EVs and renewable resources in power networks. The control of power flow and power factor correction is achieved with the full-bridge grid-tied inverter and battery current regulation is obtained with the isolated dual active bridge. The proposed control architecture of EV charger with As the requirements of power rating increases in an EV's energy storage system, it raises the need to develop an interleaved technique (Series or parallel linkage) in the boost converters. The benefits of employing the interleaved boost converters in high power applications include reduced inductor size, better performance, double switching frequency, increase power conversion density, reduce EMI, partial cancellation of input and output ripples, minimize high frequency ripples of the output capacitor, reduced conduction losses and higher efficiency. However, there are some drawbacks including complex control circuitry, reverse recovery losses of boost diodes and heating issues for input diode bridge [36]. Reverse recovery losses create heat problems at the input rectifier and limit application of this converter for 3.5kW charging power level. Therefore, soft switching techniques are implemented, and faster reverse recovery diodes are utilized in power converters to minimize the reverse recovery losses, which lead to higher efficiency [58]. The introduction of a new topology, which is a combination of bridgeless and interleaved topologies called as Bridgeless interleaved (BLIL) boost converters. The BLIL converters achieve lower EMI due to interleaving concept and higher efficiency because of the removal of boost diode rectifier bridge [57]. BLIL retains the similar number of semiconductors devices as interleaved boost PFC converter. However, BLIL needs two extra MOSFETs and two fast diodes in comparison with four slow diodes which are utilized in bridge section of the interleaved boost PFC converter. Table IV [36], [56], [57] summarizes the comparison of better and poor properties of different front-end ACDC converter with PFC for EV battery charging. Quantitative specs of various PFC based AC-DC boost topologies are summarized.

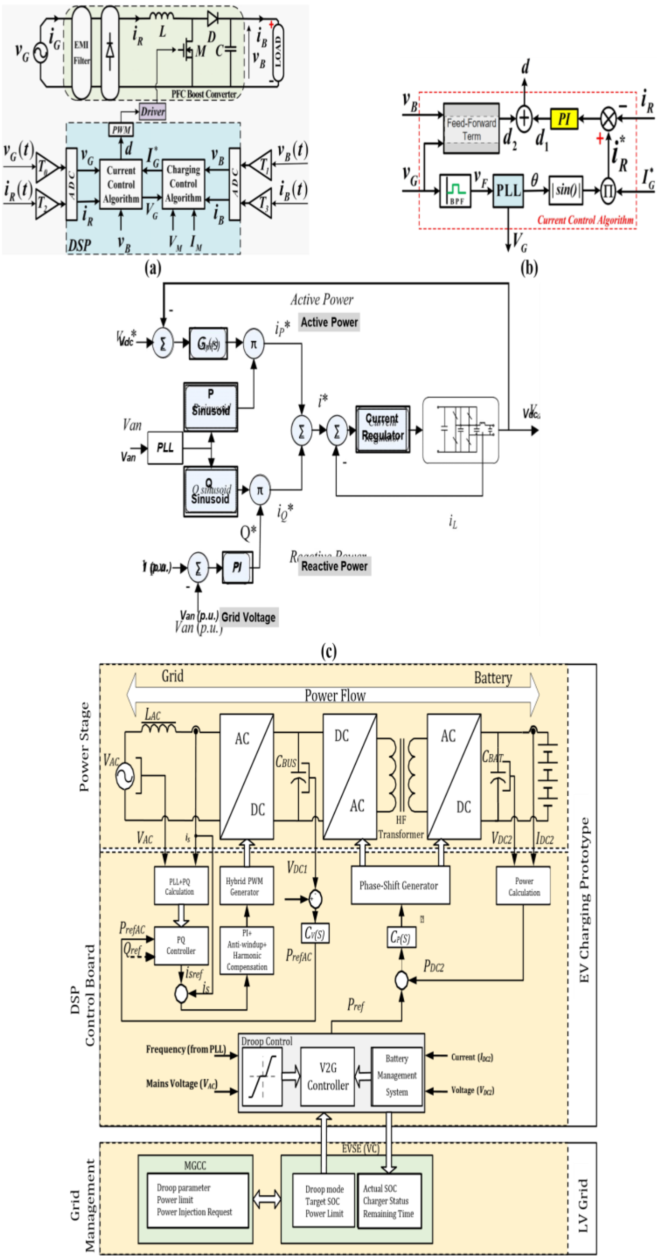


FIGURE 3

3. ISOLATED AND NONISOLATED TOPOLOGIES WITH VARIATIONS

3.1 Isolated Full-Bridge Converter Topologies with its variations: Among various converter configurations, the current and voltage fed bridges, a suitable combination of both and resonant converters with different variations are the best appropriate and mostly utilized DC-DC replacement of switches with MOSFETS enable to convert unidirectional converters to bidirectional converters. One famous topology is the combination of current-and voltage-fed full-bridge (VCFFB) converter topology, where ZVS used for current-fed side and for voltage-fed side either ZCS or ZVS can be attained [24]. The schematic illustration of full-bridge DC-DC converter is represented in fig.5(a).The DC-DC power converters usually required to operate at high switching frequencies to gain higher power densities, however, the increase in switching frequency of a transistor not only rise the total switching losses and also decrease the supply efficiency. With the rise in switching frequencies, the turn-on/turn-off losses (Switching losses) of semiconductor devices become higher. Therefore, ZCS and ZVS techniques are implemented to allow the operation at higher frequencies, while reducing the switching losses, increase the efficiency and lower the cost and size, which outcomes in higher power densities. These switching techniques also improve the converter reliability by lowering the stress on the switching devices. Another topology related to full-bridge configuration is the PSFB converter used in high power applications. The topology is same as the traditional full-bridge converter; however, the control method is different; it implements the zero voltage transitions (ZVT) and ZCS combinedly (ZVZCS) while maintaining the switching frequency constant [48],[50],[62],[63]. The oscillations can be reduced by shifting the phases of a gate pulse for switches S3 and S4 in accordance with switches S1 and S2. For both lagging and leading leg switches, zero voltage and zero current switching can be realized over a particular level of power. The transformer is used in such kind of converter topology to provide galvanic isolation [55]. Reduced switching and circulating conducting losses, PWM control and less current stress are the benefits of this topology, which makes its efficiency higher for several load conditions and a wider range of output voltage. So, it becomes one best dc/dc converter option that is appropriate for high input voltage, high frequency and high- power applications due to the afore-mentioned advantages. The main issues reported in PSFB topology are: 1) Higher circulating currents, 2) Secondary side hard switching, 3) Light load efficiency, 4) Small effective duty cycle, and 5) Secondary side switching losses and voltage stress

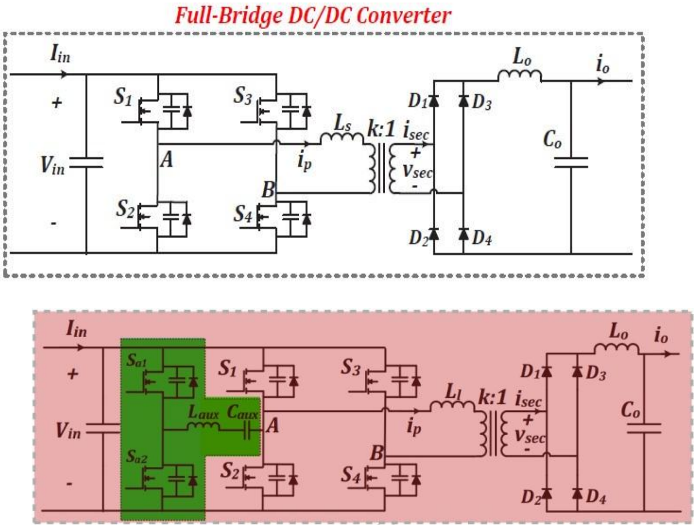


FIGURE4.

As a result, higher-order resonant converter topologies fulfil the need by presenting more required and preferred characteristics such as a capability to utilize all parasitic elements of the circuit effectively containing capacitances and inductances of the elements and using them as resonant elements, in comparison with LLC converter topology. Furthermore, the designers feel free in the designing process due to the wide range of elements available in high order resonant converters[95],[96]. Currently, these high order resonant converters are utilized in several industrial applications such as: Power supplies with high DC voltage, AC distribution systems with higher frequency .A new multi-resonant converter topology for EVs battery charging application named as L3C2 resonant converter is proposed in [66] and shown in fig.6(e) with relevant parasitics, where the parameters of the topology are: 1) Lext: External series inductance (H), 2) Llk,p: Transformer primary leakage inductance (H), 3) Llk,s: Transformer secondary leakage inductance (H), 4) Lm: Transformer magnetizing inductance (H), 5) Lp: Parallel resonant inductance (H), 6) Ls1: First series-resonant inductance (H), 6) Ls2: Second seriesresonant inductance (H), 7) Cj: Diode junction capacitance (F), 8) Cp: Parallel resonant capacitance (F), 9) Cs: Series-resonant capacitance (F), 10: Cw: Winding capacitance of the transformer secondary side (F).

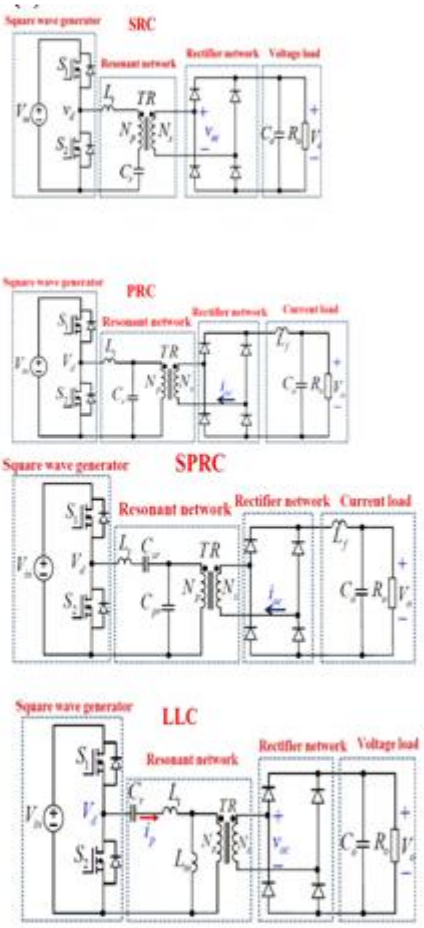
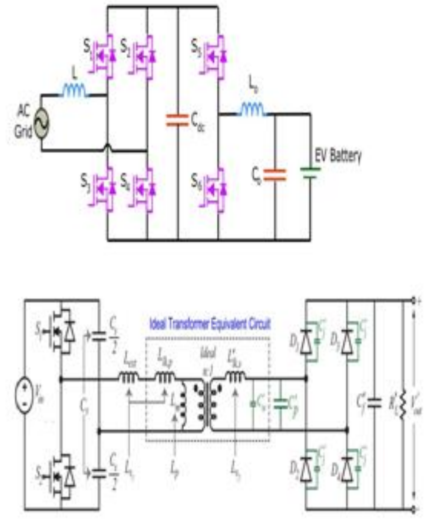
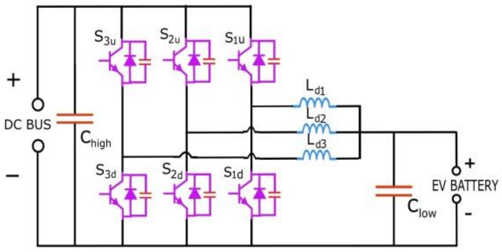


FIGURE5. Resonant Converter Topologies (a) Series Resonant Converter (SRC), (b) Parallel Resonant Converter (PRC), (c) Series Parallel Resonant Converter (SPRC), (d) LLC Resonant Converter Topology, (e) L3C2 Resonant Converter Topology.

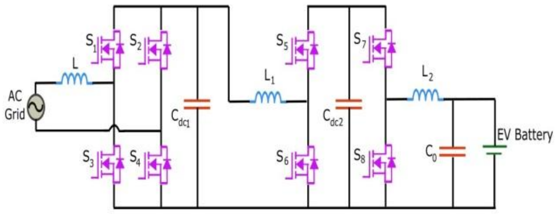
The converter configuration proposed in [105] is a half-bridge bidirectional converter as shown in fig.7(c). The converter topology is implemented with interleaved technique and intended to work in discontinuous current mode (DCM) to reduce the size of an inductor. However, the current of inductor moves towards the negative side before it tends to rise again; which is not like pure DCM mode. The complementary control structure of a gate signal is used to achieve the soft switching (turn on), so the direction of current changes, and it passes through the anti-parallel diode of the switch that is not active at that time. However, lossless snubber circuitry is attached among the switching elements to implement the turn-off soft switching. The size of an inductor as well as the input current ripple is reduced by employing the interleaved technique. The benefits which can be achieved with complimentary control switching structure are: 1) High switching frequency operation and, 2) Heat Sink size is reduced. Turn-on/Turn-off losses are optimized with proper designing of snubber capacitors and inductors. Additionally, imbalance situation regarding charging and discharging would occur in the circuit if proper parametric design values of snubber capacitors and inductors are not chosen.



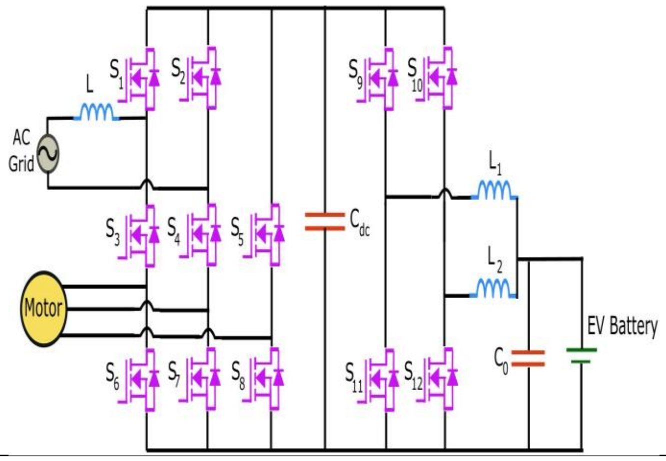
(a,b)



(c)



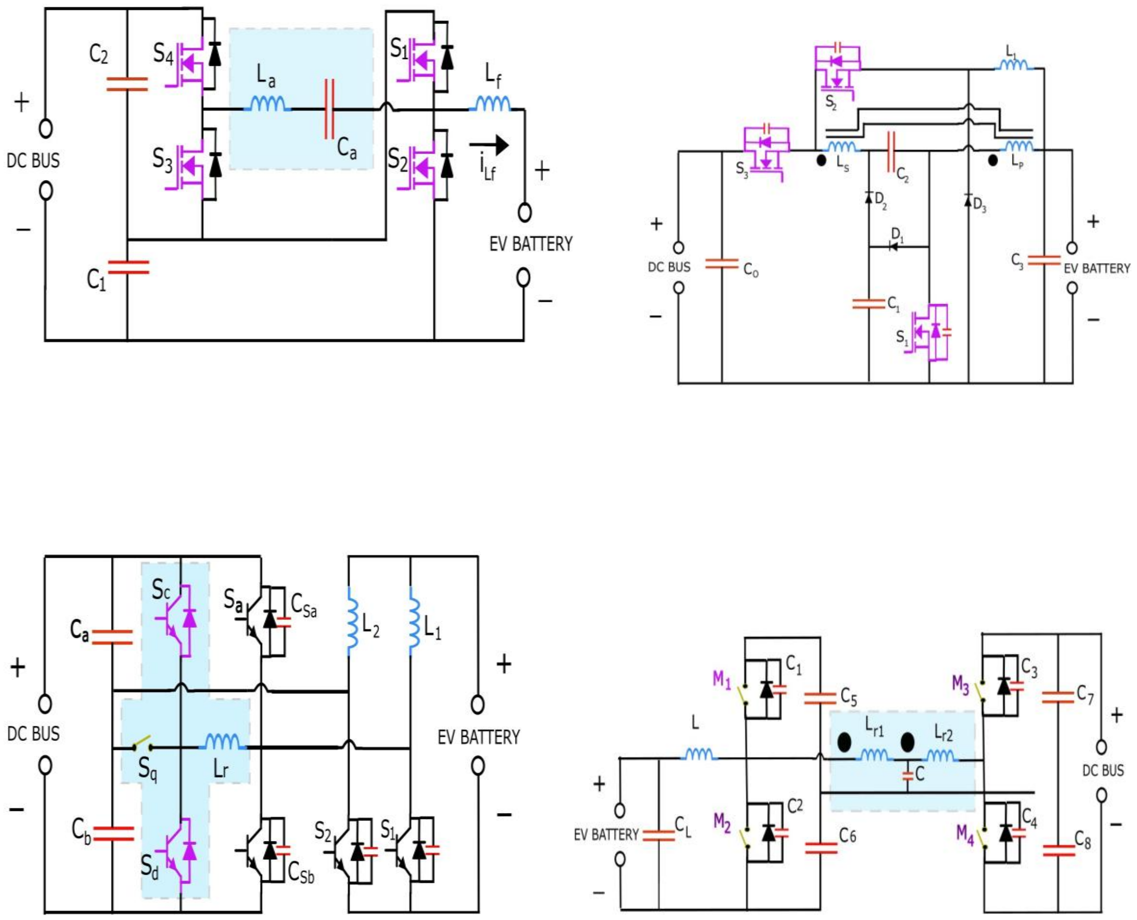
(d)

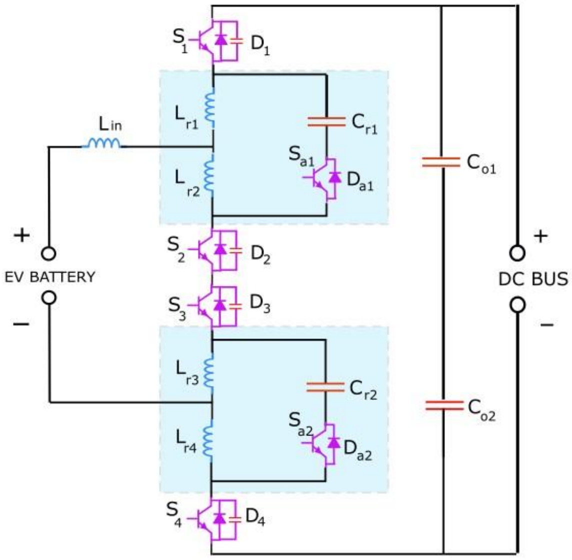


(e)

FIGURE 7:(a) Non-Isolated Bidirectional DC-DC Topology, (b) On-Board Non-isolated Bidirectional Charger, (c) Bidirectional Converter Topology with Interleaving, (d) Bidirectional Charger with Cascaded Buck-Boost Operation, (e) Bidirectional Integrated Charger

The converter topology proposed in [109] and presented in fig.8(a) is a bidirectional DC-DC converter with higher voltage conversion ratio. The converter has the capability to manage a larger amount of power in charging and discharging modes of operation (Buck & Boost). It can operate under a wider range of voltage. The soft-switching operation can be realized including ZVS and ZCS with an auxiliary resonant circuit composed of La, Ca and auxiliary power switches. The Buck and boost mode of operation can be observed with the direction of current in the inductor i.e.(iLf). The voltage ripple can be reduced by adopting the interleaved technique. However, the converter topology has more conduction losses as resonant elements are in the path of power flow for a major portion of the operating cycle. The converter topology suggested in [110] and shown in fig.8(b) has higher efficiency, which is achieved by implementing the soft-switching technique using an auxiliary circuit. The auxiliary resonant circuit is composed of a resonant inductor with power switches as shaded in the diagram. To minimize the conduction losses and to control the peak current of an inductor, the converter is operated in a continuous current mode. The soft-switching technique either ZCS or ZVS is implemented to lower the current and voltage stresses on the switching devices. The interleaved technique can be implemented to reduce the ripple current and an inductor size. However, reverse recovery losses lower the efficiency for higher power applications.





4. POWER ELECTRONICS CHALLENGES IN TRANSPORT SECTOR

The development of EV propulsion system is largely depending on power converter topologies, switching devices, and associated electronic circuits. The technology involved is diversified aiming to achieve maximum efficiency, affordability, controllability, reliability and power density. Power converter topologies vary with the type of motor to be driven. Regardless of the advancement in converter topologies, still conventional power converter topologies are popular in modern EVs. Currently, the significant purpose of providing fault-tolerant, reliable and high-power quality transfer in EVs is achieved by the applications of rectifiers, converters, and inverters at different stages. Several significant parameters are required for the development of more efficient EVs such as: 1) Appropriate selection of semiconductor devices, 2) Converters/inverters with control and switching strategies, 3) Individual unit packaging, and 4) System integration. Power electronic unit (PCU) consists of several other components including bus bars and thermal units in addition to semiconductor devices and controllers. Combining all of these into a single packaging unit as one system faces major challenges. The EV propulsion system based on power electronics technology with PCU must be highly effective to enhance the range of EV fuel economy and its electric operation. The considerable challenges in the field of power electronics regarding EV propulsion system are based on achieving a rugged, small size, highly efficient, and low-cost converter/inverter for controlling a three-phase electric machine. Semiconductor power devices with related control systems and electronic components need to endure extreme vibrations and thermal cycling. DC/DC convertors are generally well established at lower cost for low power applications. On the other hand, for high power applications still there are difficulties in achieving EV standard specifications for packaging and reliability as well as standards for electromagnetic compatibility and electromagnetic interference. Several new developments from the basic level of the device to the system level are essential with proper handling of major technical challenges to fulfil various needs of the automotive environment. Major considerations needed for appropriate selection of packaging methods are: 1) Safety standards, 2) Compliance with EMI standards, 3) Requirements for heat dissipation, and 4) Proper manufacturing design with long-term reliability. Extraction of heat in a cost-effective manner from power semiconductor devices is one significant challenge in terms of proper packaging design for converter products.The successful deployment of power electronics technology for transportation system (EVs and HEVs) is based on achieving the maximum power density and a compact package of power converter/inverter. Thermal aspects need to consider significantly to achieve maximum reliability. Thermal properties of EV chargers are generally defined by the amount of dissipated power from the installed electric components, which is around 250W for a 3.3kw level 1 charger (15Amps, 220V). In case of multifunctional integrated chargers, thermal management is easier due to a common heat sink which further reduces the overall weight, size and cost. Power density lies in the range of 10-30W/cm2 for basic level 1 charging. For higher charging levels (Level 2 and level 3), the battery size and charging power increase with an increase in vehicle range, size and speed. Consequently, thermal management of EVs becomes difficult, which can be controlled by improved battery thermal management systems. Thermal engineers must consider the vehicle design in early stages, so all the heat loads including converters/inverters and batteries can be managed efficiently. Quantitative specs including weight, size and power density of EV chargers become crucial parameters; converter topologies with several control strategies may not be adequate to meet the high-performance targets [30],[24],[144],[145],[146],[147],[148],[149],[150].

5. CONCLUSION

This paper thoroughly examines the present needs, recent development and challenges issues associated with power electronics converters to suggest possible improvements in charging solutions of EVs. The advancement in power converter topologies brings considerable improvement to EV charging technologies for electric transportation. This paper highlights the international standards, which are applied for massive deployment of EVs. In particular, an extensive analysis of front-end along with back-end converter topologies is presented with their corresponding issues and benefits. Comparative properties of front-end converters with PFC for EV battery charging are presented. Moreover, a detailed comparison of several DC-DC converter configurations and key issues of full-bridge converter topologies along with soft-switching auxiliary circuits are explained in detail. A comparative analysis of resonant converter topologies with special emphasis on benefits and issues of LLC resonant topology are addressed in this study. Furthermore, isolated and nonisolated topologies with soft switching techniques are classified and rigorously analyzed with a view to their respective constraint analysis. Additionally, the charging topologies with integrated chargers, front-end (ACAC) and back-end (AC-DC) converters are discussed. Quantitative design specs of several topologies are presented. Power electronics challenges exist in the transport sector are further highlighted. Current EV research in more than one sub-areas corresponding to power electronic converters is comprehensively analyzed for the electrification of a transportation system. It is foreseen thatthis paper would be a valueable addition and a worthy source of information for researchers exploring the area of power converter topologies in EV charging systems.

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