

# Realistic Power Electronics Converters for Electric Vehicles

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**Abstract**—Increasing the carbon emission in environment has become a major concern for the government. For promoting a clean and green environment with reduction in carbon emission by vehicles, the Government of India aspires with 100 percent electric passenger vehicle mobility by the year 2030 in the country. There is an essential requirements for fast charging stations to meet this demand as large numbers of electric vehicles to be running on the roads. In this paper, we review the state of the art in electric vehicles (EVs) charging topologies which will be necessary to support future EV refueling. Some power converter topologies are also reviewed appropriate to deliver the fast charging. DC-DC universal converter is unified converter for charging the battery and power management on buck/boost plugin operations of EVs. SiC and GaN devices are attractive to be used in the fast charging due to lower switching loss, faster switching frequency and higher operating temperature.

**Index Terms**— Electric vehicle, fast charging topology, SiC devices, GaN devices, power converter.

## I. INTRODUCTION

Transportation sector is one of the substantial contributor of greenhouse gas emission and oil consumption in the world. Road electric mobility can help in reducing significant carbon emission and anticipated energy demand due to the better efficiency compared to the Internal Combustion engine vehicles. So the Governments, automobile industries and energy corporation around the world are making the great efforts to successfully deploy EVs. The development of fast charging infrastructure for electric vehicles has become a subject of central importance in arising economics like India.

The charging infrastructure needs to be compatible with the EV battery system and classified as either a fast charger or a slow charger depending on the power handling capability. Typical architecture of an EV charging system is shown in figure 1. Battery chargers can be implemented inside (on-board) the vehicle or outside (off-board) the vehicle. On-board battery chargers having some limitations in terms of size, weight and volume, so they are compatible with level 1 and level 2 chargers. On the basis of the power ratings, EV battery chargers can be divided into level 1, level 2 and level 3. Table No 1 summarize the characteristics of the three different power levels. Level 1 charger is utilized for charging using a household grid power for overnight charging. The fast charger- level 3 charger handles approximately 50 kW to 350 kW of power and quickly charges the EV in less than an hour. Moving to an electric transportation model, it requires the battery storage competent of supplying

the energy and power demands of the vehicles. State Li- ion battery technology has modern significantly over the last years because the cost of the batteries has fallen continuously. In spite of huge improvements in energy density of these batteries with higher efficiency, the range of driving is shorter than the range of an EV on one charge than the conventional fuel vehicles. Some of the state governments also declared sufficient subsidiary amount to purchase an EV including two wheelers and four wheelers making EVs more cost effective and practical.

TABLE I. DIFFERENT POWER LEVELS FOR CHARGING

| Power Level | Charging Time | Typical Use  | Charger Location | Typical Power Rating |
|-------------|---------------|--------------|------------------|----------------------|
| Level 1     | 3- 11 hr      | Home         | On board         | 3 kW                 |
| Level 2     | 1-3 hr        | Public Place | On board         | 15- 20 kW            |
| Level 3     | 0.5 to 1 hr   | DC Fast      | Off board        | 50- 300 kW           |

Selection of the correct charging method is also to be considered with charging technology while vehicle has to be charged. To recharge the Lithium-ion battery, most feasible methods are constant current/constant voltage (CC/CV) and pulse current charging methods. Negative pulse charging method can also to be used with the pulse current charging method.

## II. FAST CHARGING STATIONS: TRENDS AND CHALLENGES

Most EVs are able to provide more than 300 km driving range on a single full charge which can cover almost every travel scenario. There is a need for a charging infrastructure which can fill up these batteries in a time comparable with the gasoline refueling. Assuming the energy consumption of 30 kWh per 160 km, on-board chargers rated at 7.2 kW would require more than 8 hours to add 320 km range to the EV (assuming the vehicle is charged at constant power). A 50 kW fast chargers still needs more than 1 hour to add 320 km, while the 135 kW Tesla Supercharger only needs 27 minutes. The recently proposed 350 kW DC ultra-fast chargers can shorten the time of adding 320 km range to 10 minutes, which is comparable to the refueling experience of gasoline vehicles [2]. According to the battery capacity, different driving range of all other models are shown in Table II with different model nos. The installation cost of the fast charging stations are very high considering the transformers, feeders, ground surface condition, conduits from the transformer to the fast charger, cost of materials and permits. As the location of the site is varying, the installation cost of the EV charger also varies. A notable portion comes into the count from the electrical service upgrades including the cost of installation and annual maintenance of protective devices like fuse, recloser, overcurrent relay etc [3].

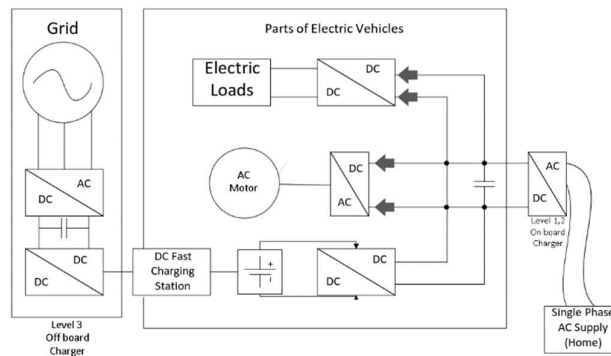


Fig. 1 Charging System Configuration of an EV

If the adoption of EVs are continued in upcoming years then it will be a likely to become a sufficient new load on the power distribution system and utility. A daily peak load will be increased and the EV charging will be uncontrolled resulting in to the overload condition of the transformer and feeder, transformer aging and huge power losses as well as deteriorate the quality of the power [4]. Power quality issues can be reduced by observing the minimum distorted utility current and high power factor drawn by the charger. Contents of harmonics must be minimized as supported by the international standards by SAE (Society of Automotive

Engineers), Institute of Electrical and Electronics Engineers (IEEE) and NEC (National Electric Code). Various standards emphasizing on the safety concerns for EVs are given in Table III.

TABLE II: EVs IN THE MARKET AND DRIVING RANGE

| Model Name         | Battery Capacity (kWh) | Driving Range (km) |
|--------------------|------------------------|--------------------|
| Mahindra e-Verito  | 21.2                   | 150                |
| Tata Nexon EV2     | 30.2                   | 200                |
| Tata Tigor         | 21.5                   | 213                |
| Hyundai            | 39.2                   | 250                |
| MG Motor ZS        | 42.5                   | 320                |
| Nissan Leaf        | 62                     | 363                |
| Chevy Bolt         | 60                     | 383                |
| Mercedes Benz EQC  | 76                     | 450                |
| Tesla 3 Long Range | 75                     | 498                |

Table III: Safety Standards for EVs [5]

| Technical Code          | Details                                                                                                      |
|-------------------------|--------------------------------------------------------------------------------------------------------------|
| SAE J-2464:             | Safety rules for recharge energy storage systems(RESS) are described                                         |
| SAE-J2929:              | Safety for EV propulsion battery system                                                                      |
| ISO 6469-1: 2009 (IEC): | Electrically propelled road vehicles, inside and outside protection of a person, on-board RESS are described |
| UL 2202:                | Protection of charging system is described                                                                   |
| IEC 61851-21:           | Requirements for conductive connection of EVs.                                                               |
| ECE R100:               | Electric shock protection.                                                                                   |
| NFPA 70/70E:            | Workplace safety, branch circuit protection, and charging system safety                                      |
| IEC TC 69/64            | Electric shock protection, EV infrastructure safety, and Electrical installation.                            |

### III. GRID CONNECTED AC TO DC CONVERTER

These converters provide the interface between the grid and regulated dc bus. Basic requirements for a high power ac-dc converters are to achieve maximum power factor with distortion less operation to avoid major destruction to power system network so that a good power quality can be achieved. It can be achieved by input current shaping and voltage regulation at output side [6]. Here three converter topologies are explained to convert AC to DC suitable for fast charging of EV as shown in fig 2.

#### A. Three Phase Pulse Width Rectifier (PWM) Rectifier

The most widely used grid facing ac to dc converter is the three phase PWM converter with an LCL filter as shown in the fig 2a. The value of the output voltage of such rectifier could be regulated among a certain extent higher than the peak value of the input ac voltage so it concern to voltage boost rectifier [7]. This converter topology is capable of constant current charging, constant voltage charging and constant current discharging. In [8], a high performance battery charger presented for EV where the result of experiment shows that the charging efficiency is higher than the 85% and the input power factor is higher than 99.3% for prototype with the rated output power of an 8 kW. Due to the simple structure, sufficient control schemes and availability of the switching devices with sufficient voltage and current ratings; this topology is adopted in the state-of-the-art of the fast charging of an EV.

#### B. Neutral Point Clamped(NPC) Rectifier

For the bidirectional power flow with less complexity and very low total harmonic distortion (THD), this boost type of converter is used for charging of EVs and it's shown in fig 2b. This converter topology enables the utilization of the devices with lower switching losses with a reasonable cost. The resulting three level waveform of the voltages reduce the input current harmonics and dv/dt rating. Direct power control proposed for three-level NPC converter where the input inductance value and size are remarkably reduced which leads to notable increase in power density [8]. In [9], the charging system of 30 kW for EV by NPC is proposed for charging of lithium-polymer and lithium-ion batteries. Also, the system is able to reach the full charge position within the 16 minutes for the battery capacity of 8 kWh by supplying the charging current of 78 ampere. A three level NPC topology allows to operate in the range of megawatt without increasing the dc bus voltages. The NPC enables operation in MV (lesser currents, smaller like a choke) and higher efficiency without compromising the quality of power [10]. Another advantage of NPC given in [10] is that ac/dc front end is explicitly creates a bipolar dc bus.

#### C. Buck Type Rectifier

If only unidirectional power flow is required and necessary output voltage is lower than the input line current then a buck type rectifier can be used and it's shown in fig 2c. This topology having some of the advantages over

the boost topology like simplex inrush current control and inherent short circuit protection as this converter is only unidirectional with fixed voltage polarity at output. However, the conduction losses are higher as many devices are connected in series but switching losses can be lesser.

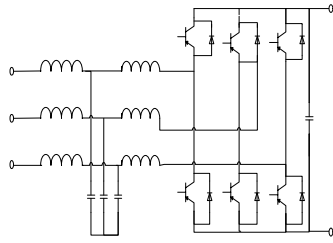


Fig 2a. Three Phase PWM Rectifier

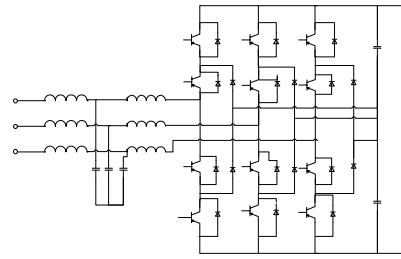


Fig 2b. Neutral Point Clamped Rectifier

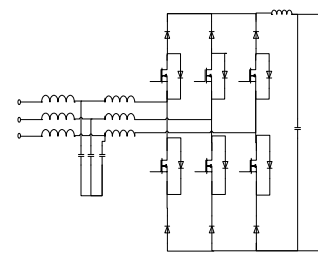


Fig 2c. Buck Rectifier

In [11], a hardware with buck topology implemented for specifications of 5 kW output power with mains voltage of 400 V<sub>rms</sub> and output voltage of 400 V with the efficiency of higher than 95%. This converter is only unidirectional with fixed output voltage polarity. For the wide output voltage range, the phase shift between the input voltage and input current needs to be kept small. A modified buck converter allows two input phases connecting to each phase leg results into the reduced conduction loss with maintaining lower THD [13]. With addition of the forth leg connecting in diode bridge to the midpoint of the diode bridge and the star point of the input capacitor leads to reduced voltage stress on every switches [14]. So it permits the utilization of the lower voltage rating switches for the better performance with higher system efficiency. Comparison of these all three topologies are given in table IV.

TABLE IV. COMPARISON OF AC/DC CONVERTER TOPOLOGY

| Converter       | PWM Converter | NPC Converter | Buck Type Converter |
|-----------------|---------------|---------------|---------------------|
| Power flow      | Bidirectional | Bidirectional | Unidirectional      |
| No of switches  | 6             | 12            | 6                   |
| No of diodes    | 0             | 6             | 6                   |
| Range of pf     | Wide          | Wide          | Limited             |
| THD             | Lesser        | Very lesser   | Lesser              |
| Controllability | Lesser        | Moderate      | Lesser              |

#### IV. ISOLATED DC TO DC CONVERTER

After the AC to DC front end converter, DC to DC converter provides an interface to the vehicle battery or the storage system of battery. A galvanic isolation is required to provide the isolation between the grid and the battery so that the battery protection remains unaffected by the charging system. This can be achieved by using an isolated dc to dc converter. The suitable topologies are presented in figure 3a, 3b and 3c.

##### A. Phase Shift Full Bridge (PSFB) Converter

For the unidirectional power flow, a manageable implementation is the PSFB converter in which the active switches operate at zero voltage switching (ZVS) turn on. The main disadvantages of this converter topology are turn off losses in switches, losses in output diodes, larger ringing across the output diodes etc, the usage of this converter is limited. With an active switch doubled current double rectifier, this converter has lower voltage stresses in the secondary side components so it can be possible to implement in on-board charger too [15]. Also some advantages are the ZVS range is extended and higher efficiency from light load to full load can be obtained. To minimize the voltage overshoot and the ringing, it is proposed that to move the output inductor to the primary side of the transformer and connecting the diode bridge to an output capacitor. In [16], using the current doubler rectifier with this converter achieves a 92% efficiency during a charging process in the constant current- constant voltage control mode for a 3.2 kW prototype.

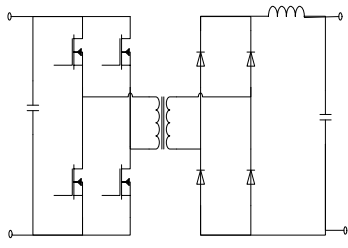


Fig 3a. Phase Shift Full Bridge Converter

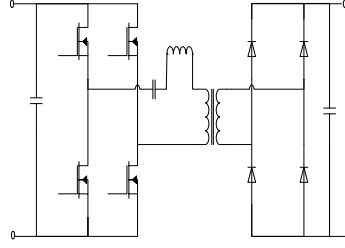


Fig 3b. LLC Converter

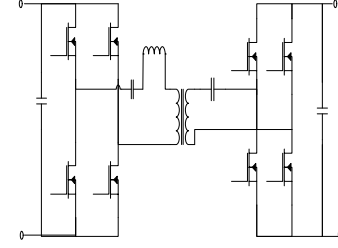


Fig 3c. CLLC Converter

### B. LLC Resonant Converter

In this unidirectional isolated DC to DC converter for charging the EV, the output voltage is regulated by changing the switching frequency to adjust the impedance ratio to equivalent load. It utilizes the magnetizing current to achieve the ZVS so the turnoff losses and transformer losses are reduced to some extent. It can achieve a very high efficiency with control the voltage ratio i.e. the ratio of input voltage to output voltage is limited. In conventional LLC resonant converter, the battery pack voltage varies in a wide range with the change of state of the charge. In [17], a slightly modified PWM LLC type resonant converter is proposed and it shrinks the magnetic component size and achieves a wide and fixed voltage gain range independent to the load condition. To improve the performance for a wide output range and at light load condition, multiple approaches are proposed. Various methods are proposed with PWM, phase shift and different hybrid modulation schemes to narrow the range of operating frequency with expanding the output range [18] [19].

### C. CLLC Converter

The bidirectional CLLC converter is known for its symmetrical circuit and smaller reactive power circulating in the converter. It gives the same voltage gain characteristics in both power flow direction tends to reduce the complexity and facilitates the power regulation. Two resonant capacitors on both the sides of the transformers help to reduce the capacitor voltage stress in compare to LLC converter [20]. It can operate under the ZVS for the primary switches and soft commutation for the output rectifier. The sinusoidal resonant current of this converter exerts lesser stress on the high frequency transformer for the prototype model of 15 kW, 500 kHz [21]. A 6.6 kW, 500 kHz charger for EV is demonstrated with the efficiency of 96% and power density of 37 W/m<sup>3</sup> [22]. Comparison of these all three topologies are given in table V.

TABLE V. COMPARISON OF ISOLATED DC TO DC CONVERTER

| Converter       | PSFB Converter        | LLC Converter                    | CLLC Converter      |
|-----------------|-----------------------|----------------------------------|---------------------|
| Powerflow       | Bidirectional         | Bidirectional                    | Unidirectional      |
| No of switches  | 4                     | 4                                | 8                   |
| No of diodes    | 4                     | 4                                | 0                   |
| ZVS/ZCS         | ZVS except light load | ZVS on primary, ZCS on secondary | ZVS over wide range |
| Switching Loss  | High                  | High                             | Less                |
| Controllability | Less                  | Moderate                         | Less                |

## V. COMPARISON OF Si, SiC AND GAN

Power electronic switching devices including wide band gap materials (WBG) such as silicon (Si), silicon carbide (SiC) and gallium nitride (GaN) provide considerable switching level improvements. Especially the ability of SiC and GaN to operate at higher voltages, frequencies and temperature make them highly qualified for use in the future power electronics. Comparison of Si, SiC and GaN are shown in Table VI. These material properties have a major impact on the performance characteristics of the devices. The high critical field of both GaN and SiC compared to Si is a property which allows these devices to operate at higher voltages and lower leakage currents. Higher electron mobility and electron saturation velocity allow for higher frequency of operation. While SiC has higher electron mobility than Si, GaN's electron mobility is higher than SiC means that GaN should ultimately be the best device for very high frequencies. SiC has greater thermal conductivity than GaN or Si meaning that SiC devices can operate at higher power densities than either GaN or Si. Higher thermal

conductivity combined with wide band gap and high critical field give SiC semiconductors an advantage when high power is a key desirable device feature.

| Material Properties                                         | Si   | SiC | GaN  |
|-------------------------------------------------------------|------|-----|------|
| Band Gap (eV)                                               | 1.1  | 3.2 | 3.4  |
| Critical Field ( $10^6$ V/ cm)                              | 0.3  | 3   | 3.5  |
| Electron Mobility ( $\text{cm}^2/\text{V}\cdot\text{sec}$ ) | 1450 | 900 | 2000 |
| Electron Saturation Velocity ( $10^6$ cm/ sec)              | 10   | 22  | 25   |
| Thermal Conductivity (Watt/ $\text{cm}^2$ K)                | 1.5  | 5   | 1.3  |

SiC and GaN devices are used extensively in the above suggested grid connected ac to dc converter and isolated dc to dc converter. The design and development of a 20 kW, 100 kHz high power density isolated dc-dc converter for battery charger is presented in [23] where SiC power module discussed and estimated the efficiency of 98% over a wide range of the output power. Based on the transistors types, the conduction and switching losses are analyzed in [24]. Conduction losses are evaluated by calculating the on-resistance and losses created by the transistor current, which is depend on junction temperature and transistor current, on every switching cycle. The dependency of turn-off and turn-on energy on gate resistor, junction temperature, transistor current and voltage was taken into account. According to the GaN data sheet, the GaN transistor does not create reverse recovery losses because GaN transistor does not have reverse recovery charge. In SiC and Si transistor, reverse recovery exists and included in the turn-off and turn-on energy. Authors evaluate the performance of an isolated dc-dc converter with output voltage of 400 V and 800 V using SiC MOSFET as a switching device for EV charging application [25]. SiC having the upper hand with the thermal conductivity while GaN with an excellent electron mobility. A unique topology is presented in [26], where the configuration of the SiC- GaN based dc-dc converter and paralleled GaN based dc-dc converter are simulated for 54 kW. So as per the power demand at a particular instant, particular leg of the converter will be conducted.

## VI. CONCLUSION

This paper reviews the different power levels of charging including charging location, charging time and power rating. Level 1 and level 2 charger topologies are usually mounted inside the vehicle forming in this way the so called onboard charger. On the other side level 3 chargers are installed off board the vehicles, in this way their collection leads to the creation of the so called FCSs which are promising candidates for future EV high penetration. The most common topologies which are suitable for each level of an EV charger have been presented. Comparisons of the grid connected ac-dc converters and isolated dc-dc converters tabulated which will be useful to select the charging topology of EVs. Finally, the silicon switching devices are expected to be replaced by wide band gap SiC and GaN devices in order to allow a phenomenal reduction in weight and volume of the power electronics charger. For the higher switching frequency, GaN is superior compare to SiC and for higher voltage rating, SiC is better than the GaN. However, to utilize the both SiC and GaN in one converter topology will results in the best efficiency and eminent reduction in the cost of the charger and definitely it will reduce the charging time of an EV.

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