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Implementation of SiC Power Electronics for Green Energy Based Electrification of Transportation

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IMPLEMENTATION OF SIC POWER ELECTRONICS FOR GREEN ENERGY BASED ELECTRIFICATION OF TRANSPORTATION

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ABSTRACT

Increase in greenhouse gas emission poses a threat to the quality of air thus threatening the future of living beings on earth. A large part of the emission is produced by transport vehicles. Electric vehicles (EVs) are a great solution to this threat. They will completely replace the high usage of hydrocarbons in the transport sector. Energy efficiency and reduced local pollution can also be expected with full implementation of electrification of transportation. However, the current grid is not prepared to take the power load of EV charging if it were to happen readily. Moreover, critics are doubtful about the long-term sustainability of EVs in terms of different supply chain issues.

The first step for tackling this problem from a research perspective was to do a thorough review of the details of charging in modern day grid. The downsides and lack of futuristic vision. Findings showed that implementing end to end DC based on green energy aided by SiC power electronics. To prove the findings analysis and modelling was done for SiC based charging network. A similar approach was implemented in EV powertrain development.

The implementation of SiC power electronics in charging network showed lesser losses, higher thermal conductivity, lesser charging time. The effect on long term battery health and additional circuit was also observed. The cost of production can be reduced by volume manufacturing that has been discussed. In powertrain analysis and simulation the loss and heat reduction one shown on a component-by-component basis.

Therefore, this research proposes a Silicon Carbide based end to end DC infrastructure based completely on solar and wind power. The pollution will further be reduced, and energy demands will be met.

ACKNOWLEDGMENTS

The completion of this research was principally supported by the expert supervising of **Dr. Rajendra Singh,** my respected PhD advisor. His enormous body of work was an inspiration and fueled my own passion for sustainable energy. Apart from technical knowledge, his management skills motivate me to become a better person every day and practice empathy. I am invariably grateful to him for his valuable guidance.

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CHAPTER ONE
INTRODUCTION

Based on 2018 data, 24 % of the global carbon emission is due to transportation [1]. About 75 % of transport sector emission comes from road vehicles [1]. Out of the 75 % emission, passenger vehicles (cars, motorcycles, buses and taxis) contribute 45.1 % and the rest is contributed by freight vehicles (trucks and Lorries) [1]. To curb carbon emission, electrification of transportation (EOT) in general and passenger and freight vehicles in particular require green and clean electrical power.

Free sources of energy, namely, solar, and wind, are the only sustainable sources of energy. With global incident solar power of 23,000 TWy/y, abundant solar power is the ideal source for generating electric power [2]. Photovoltaics (PV) and battery-based networks can provide sustainable electric power at ultra-low cost for almost all over the world except for few places where solar intensity is less than about 3-4 kWh/m^2 per day [3]. In those place wind turbines can be employed and PV can play a complimentary role.

The International Energy Agency declared in 2020 that solar power is the cheapest form of energy at $0.02/kWh at utility scale. In future, improvements such as glass manufacturing co-located with PV manufacturing can provide cost of PV energy production routinely of one cent per kWh or less, as recently demonstrated in Saudi Arabia [2]. For EOT, batteries and the use of hydrogen to convert electric power by fuel cells are the two main choices of using electric power in EVs. There is no reason that we cannot build a charging station capable of charging 500KM range in less than 10 mins. In addition to technology complexities and high cost, the energy efficiency of hydrogen-based vehicles is much lower than battery electric vehicles (BEVs) [4]. Charging stations capable of powering up five electric semi-trucks at a time use the power of 10MW, lesser than the power required by many urban areas. So there could be a possibility that charging station installation might not mean power grid upgrade.

For long-haul electric trucks, battery technology is technically feasible and economically compelling [5]. The only issue in installing charging stations remains now the government policies, clean energy rebate etc. Due to mass scale production and advancements in technology that include increase of power density, the cost of batteries is falling rapidly, and the EV cost is going down every year [3]. A study reveals the cost of Li-ion batteries have gone down 97% since they were introduced in 1991. The rate of development in Li-ion batteries has been almost as exceptional as solar panels since its inception. Since 2010, the average price of a lithium-ion (Li-ion) EV battery pack has fallen from $1,200 per kilowatt-hour (kWh) to just $132/kWh in 2021[6]. Technology like Megapacks can be storage for grid and also for independent storage needs [6].

Over the time industry is more reliant on storage as they are using storage for almost double the time in average to operate their shopfloors. Despite all these advancements, lack of research in the particular area of power electronics for XFC and powertrain seems the primary roadblock for implementing ultra-low cost extremely fast charging (XFC) infrastructure in a large scale EOT. The existence of AC grid is a hindrance to end to end DC power-based networks. Despite DC being more power efficient, more compatible to green energy resources, all the device electronics operating in DC power, energy storage is completely DC, yet the power grid being AC is wasting valuable electricity.

There also lies the issue of the current industry based on Si power electronics as it is cheaper whereas SiC technology is delivering higher voltage operation, wider temperature ranges and increased switching frequencies. The motivation of this research lies in implementation of green energy based end-to-end DC power (in place of current AC power-based infrastructure) and the use of silicon carbide based extremely fast chargers and powertrain. These have the potential to provide ultra-low-cost charging infrastructure. Moreover, replacing the powertrain with silicon

Carbide will make the EVs capable of receiving the fast charging without additional weight. Thus in addition to DC power-based electricity infrastructure, there is an urgent need to develop an ultra-low-cost DC power based SiC-XFC and SiC based Powertrain.

Despite this, the fast-charging technology is not without its limitations. In the second chapter the technology gaps in EV fast charging stations mostly focused on the extremely fast charging topology has been identified. It will help pave a path for researchers to direct their effort in a consolidated manner to contribute to the fast-charging infrastructure. A thorough review of all aspects and limitations of existing extremely fast charging (XFC) stations have been identified and supporting data are provided. The importance of DC power network based on free fuel energy sources and silicon carbide-based power electronics are proposed to provide ultra-low cost and ultra-high speed XFC stations.

The use of larger size silicon carbide wafers will further reduce the cost of power electronics based on silicon carbide. Use of green energy sources (solar and wind) and lithium-ion batteries for electrical power storage can provide end to end DC power networks. Such networks combined with silicon carbide based XFC of EVs can play a revolutionary role in saving green electrical and provide reduced charging of EVs. Chapter Three reports almost 50% reduction in power losses by using Silicon Carbide DC technology. End to end DC power networks combined with SiC based XFC of EVs can play a revolutionary role in solving climate emergencies.

Chapter Four analyses an 800V EV powertrain using UnitedSiC UF3C170400K3S. To implement this higher-powered train in vehicles, the complete reconsideration of the electrical system is imperative. This chapter analyzes the implementation of Silicon Carbide based Power electronics to operate an 800V powertrain and evaluate it against the 800V Si powertrain in depth including details like drivetrain, inverter, auxiliary power units in high voltage CharIn charging (Megawatt Level) system.

Chapter 5 discusses the pros and cons of the future of charging and powertrain trends and the future scopes of this research. The limitations in current trend and the industry forecast were discussed. The end-to-end DC green power is the only solution and going forward the premise of this research needs to be based on that aspect.

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CHAPTER TWO

A REVIEW OF EXTREMELY FAST CHARGING STATIONS FOR ELECTRIC VEHICLES

Introduction

Worldwide awareness on climate related challenges and sustainable mobility, motivated to control the emissions from the gasoline-powered internal combustion engine vehicles (ICEVs), which constitutes 16.2% of the total emission worldwide [1]. Apart from ground transportation via passenger cars, the heavy-duty commercial vehicles constitute a major number of electric vehicles in usage today. Lightweight Battery electric vehicles represent only 2.5% of total vehicle sales [2]. The same can be said for the aviation and marine industry where they have the potential to be electric or, as in the case of ships, are already electric but use fossil fuels to generate power on-board. Replacing these vehicles with battery vehicles for all three modes of transportation can bring a sharp reduction in carbon emissions. Several applications in aviation and ground transportation have been advancing at a remarkable pace due to the progress of electric motors, power electronics, and batteries etc. This has contributed to the commercial take-off of fully electric transportation. According to UBS estimation, the aviation industry will be 25% hybrid or fully electric by 2035 [3]. It is also hard to standardize safety measures and requirements in air and maritime transportation due to regulations and cross border operation. Therefore, it might be safely concluded that battery electric vehicles (BEV) are making ground transportation the pioneer of electrification of transportation [3]. To implement this, the following are the key requirements: (i) the upfront cost and cost of ownership of electric vehicle must be equal to or less than ICEVs, (ii) the range of electric vehicles (EVs) must be equal or greater than ICEVs, and (iii) green energy must be used to create extremely fast and low-cost charging infrastructure. Industry is making great progress addressing the first two points. As an example, Tesla is planning to introduce 25,000 EVs USD [4]. Although the industry is doing their best work to provide low upfront cost and high range, the implementation of green and sustainable energy is yet to be seen on a large scale. Therefore, the objective of this paper is to review the key challenges that have the potential to implement sustainable green energy as the source of electric power and silicon carbide power electronics for wide range implementation of electric vehicles at large scale. There are currently four levels of charging in industrial usage. The IEC 61851 describes the first three levels are AC charging ranging from 250 V (1P), 250 V (1/3P)–480 V (1P) and 480 V (3P) respectively [5]. Clearly, none of these satisfy the need for extreme fast charging needed for heavy duty vehicles. 250 V and 32 A will produce 8 kW whereas the thermal equivalent of one gallon of gasoline is 35 kWh [6]. According to EPA (Environmental Protection Agency) guidelines 35 kWh must drive at least 99 miles. Therefore, transferring a similar amount of energy in terms of an EV will require 4.5 h of charging for a mid-range sedan like Nissan Leaf which is impractical [7]. As level 1 and level 2 charging is widely implemented, we have reviewed the DC fast charging and pointed out the fundamental changes required to accelerate the electrification of surface transportation. Recently, Tu et al. (2019) have published a review article [8], however the article had limited coverage that mostly focused on the several power electronics architectures and not much on the other aspects like review of cyber security measures and protection design. That provide the pathways to low-cost XFCs. The authors of reference [8] don't delve into the subject of DC grid or silicon carbide power electronics for fast charging. In reference [9], emphasis is placed on the charging equipment and inductive charging. The scopes of inductive charging remain doubtful economically for heavy duty vehicles because of their high losses. Similarly, in reference [10] all levels of charges are reviewed, but less emphasis is given on fast charging as the need of the hour. Another review paper focuses solely on the charging standards while the technical aspects are barely mentioned [11]. The focus of reference [12] is on DC fast charging but only on energy storage design and not power electronics. The emphasis of this review paper is on relevant power electronics technologies of DC fast charging and other aspects such as cyber security, protection, and impact of DC power green sustainable electrical power networks and the role of silicon carbide power electronics in fast deployment of XFC on a large-scale basis. The main problems addressed will be the high losses occurred during power electronics conversion, the poor state of DC protection, and the gaps in cyber security measure. In this article we have provided a potential solution to all the questions by researching existing resources and proposing the best-case scenario results. The novelty of research lies in the comprehensive solution provided in every aspect of charging station which is not found in current literature as mentioned above.

Background Information:

Label conventions define that equipment which is continuously operating above 150 kW are considered extremely fast charging (XFC) [8]. In general DC fast charging may be harmful to the EV battery due to thermal issues. Repeatedly heating the battery from DC fast charging is thought to accelerate battery degradation over time. To mitigate this, some EV manufacturers have suggested that EV owners refrain from using DC fast charging every day. The new On-Route Battery warmup introduced by Tesla prepares the battery pack thermally by automatic software before arriving at a Supercharger station. The navigation system detects the driver’s commands to be redirected to the Supercharger station and the thermal preparation gives peak charge rate faster and longer while parked at the station [13]. A complete consideration of industry standards, grid impacts, and other technical policy issues need to done before implementing such a complex EV charging infrastructure.

The block diagram of DC extremely fast charger is shown in Figure 1 [14] which is connected to the grid. Since our existing electricity infrastructure is based on AC, components shown in blue color within red square are required to convert AC input of the grid to DC input power of XFC. These components are not required for DC grid with the net result of cost reduction of XFC and a higher system reliability (due to less number components in the system). Thus, an important aspect of background motivation lays in the end-to-end DC.

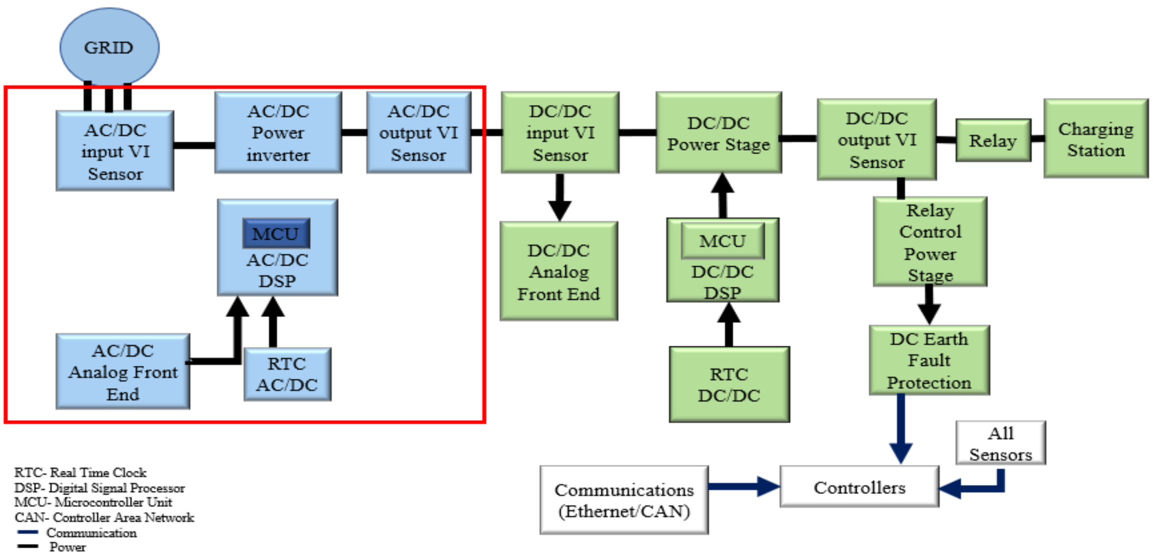


Figure 1 : Block diagram of DC XFC Charger connected to the grid [14].

Infrastructure as shown in Figure 2 [15]. The transmission losses caused by AC-DC-AC conversion can simply be averted by adopting a fully DC system. But the current XFC infrastructure being AC, lacking this opportunity. More on this has been explained in the discussion in Section 13.

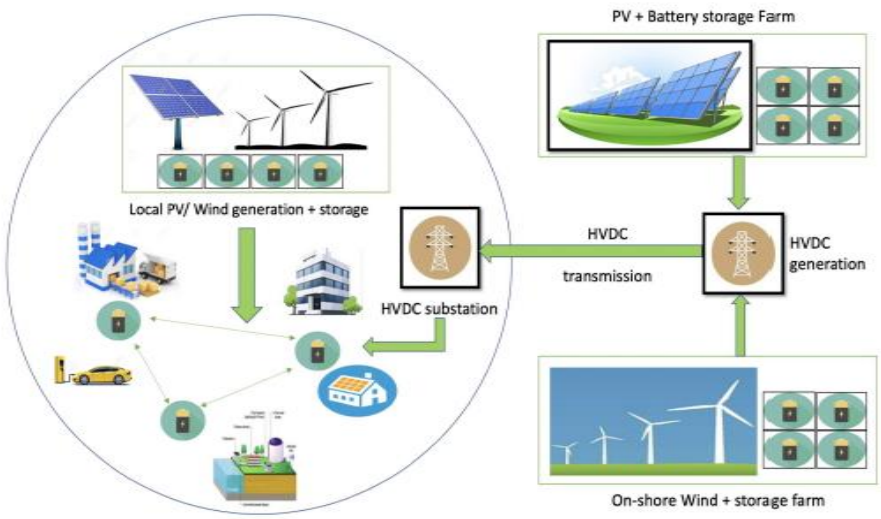


Figure 2 100% DC Grid Powered by PV, and or Wind and Battery [15].

The heavy-duty charging cable has additional maintenance issues as they are made of bulky liquid cooled assemblies. The MW level charging cable must be in between 1000 to 1500 V and 1000 to 3000 A. The safety issue in MW level is more important than level one and level 2 charger to protect equipment and personnel [16]. A new kind of fault due to the high voltage present on wye capacitor filters occur in this level as well. The lack of clear guideline based high voltage level charging, makes the job of infrastructure harder. In case of renewable integration of MW level charging, their sources like PV or wind must be coupled to a common DC bus. Hence, research is also necessary on the mechanical side to identify how many parallel modules can be connected on each energy node. In case of the DC-to-DC converters they will need additional charging intelligent controllers to coordinate the usage of charging nodes for multiple vehicles relying on the same charging power.

The summary of currently available chargers is given in Table 1. It is evident that there is an urgent need of extremely fast chargers (XFCs).

Table 1: Types of Fast Charger available as of Now [8].

Type of Fastest Charger Available in Market	Power (kW)	Efficiency	Time to Add 200 Miles
PHIHONG Integrated type	120	93.5%	30 min
Tesla Supercharger	135	91%	27 min
EVTC espresso and charge	150	93%	24 min
ABB terra HP	350	95%	10 min

Several problems cloud the possibility of a widespread XFC charging station network. The heavy load on the grid during fast charging hours remain one of the biggest concerns. Designing the correct algorithm as mentioned in reference [17] is the biggest engineering problem that remains to be addressed in the fast-charging scenario. In retrospect, the authors of reference [15] propose a battery and photovoltaic based charging network for this specific purpose so that the charging infrastructure remains completely separated from the AC grid and the load is minimized. The scope of this paper is to point out the advantages of DC charging and the dependence on solar and or wind as energy sources with batteries incorporated is a new perspective to minimize the stress on an already overloaded grid.

Extremely Fast Charging Station Infrastructure:

The sustainable option of EV is ignored by the masses due to the time of replenishing the fuel (Electricity) in them. Consumers are accustomed to the idea of visiting the gas station, refueling their cars in 5 min, and getting back on the road. Once fueled, a typical Internal Combustion Engine Vehicle (ICEV) runs 300 to 400 miles making that technology lucrative. Thus, the sole focus of EV charging station placement and planning research must be on making the charging stations more like gas stations. The existing fast charging architecture needs service transformers to be connected to the Medium Voltage (MV) line, that adds up to the size, cost and has a complicated installation process thus increasing labor cost as well [18]. More light on cost analysis of XFC is shed on Section 7. The prevalent EV charging technology are level 1 and level 2 which can be found at home or workplaces. An average American travels approximately 30 miles per day, spending about 46 min in commute [19,20]. Therefore, the level 1 and level 2 charging are serving adequately for their day-to-day need. However, the long-distance trips in EVs still remain a challenge. Unplanned trips or days where there might be a sudden blackout or power outage also need to be considered for the EV to go uncharged a few days. To eliminate this problem XFC is an essential technology. Other than serving in the earlier scenarios, XFC can be a boon in multiunit dwellings in metropolitan environments, the long-distance commercial transport as buses, trucks or other shared fleets will also benefit from XFC as those vehicles are bigger and need more kWh of power and more time to charge from level 1 or 2 charging thus making their charging prolonged at present [20].

Grid Stability:

The heavy load imposed on power grid during charging is a big challenge yet to be addressed. Recent XFC technologies are capable of even drawing 350 kW for one single car [6]. When the heavy-duty vehicles with 1.2 MW battery pack are commercialized the fast-charging voltage level will go even higher causing a negative impact on the grid. Although the growth of EVs and their associated charging stations has a positive impact on the environment and related economic growth, it can have detrimental effects on the power grid [21]. These effects need to be understood before moving to possible remedies or ways to mitigate them. Increased peak demand, reduced reserve margins, voltage instability and reliability problems are some of the challenges associated with High charging load derived from fast charging. The probable solutions to these problems are analyzed below.

4.1 Smart Charging:

Smart charging intelligently manages the EV charging without destabilizing or overloading the grid. It enables opening pathways by the utility companies and charging operators to communicate with each other. Depending on the load on the grid these smart chargers will increase or decrease the power supplied to the charging stations [21]. A network operator will have the ability to regulate the flow of power to the stations depending on the load on the grid. This enables features like power sharing, power boost and dynamic power sharing. Although a promising solution but the drawback of human error is the main concern.

4.2 Vehicle to Grid (V2G):

With renewable integration, the V2G algorithm is a useful strategy to maintain grid stability. The operating principle is akin to smart charging but here the grid is the master and charging station is the slave in this two-point operation. It also enhances the grid's ability to self-balance.

This is imperative when renewable resources are integrated in the AC grid [21]. Without V2G long distance transmission costs will increase as energy from farther reserves will be needed to transport power thus raising the tariff. The critical drawback of this system is the availability of reserved power at a certain location and the associated transmission cost. A minutely detailed algorithm operating accurately is imperative for the success of V2G operation. For Level 1 and Level 2, V2G is already showing promising results. However, their effectiveness in XFC is yet to be analyzed on a large-scale system. To stabilize grid, separating it from charging network remains the most efficient solution.

4.3 A Microgrid Ecosystem

The correct amalgamation of microgrids instead of a large power network is good solution to the problem of grid stability. Defined by power utilities, "A microgrid ecosystem is a locally interconnected system with clearly defined electrical boundaries" [21]. It has several advantages as follows:

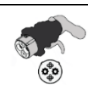
- Integrates loads and distributed energy resources, including BESS.
- Compound power generating resources.
- Both grid-connected and be off grid.
- A single unit with its own autonomous control in both approaches.
- Several kilowatts to multiple megawatts with a voltage range up to megavolts can be the power range.

Globally, utility companies are welcoming charging infrastructure, because it is a revenue generating business model with long-term turnover. However, haphazard installation of charging stations to fulfill ever growing demand might destabilize the grid. Therefore, it's imperative that the utility companies develop a comprehensive Electrical Service Requirement (ESR) documentation for the charging companies stipulating the boundaries. In conclusion, the energy management and grid stability are a growing research area and authors here have aimed to summarize the efforts for a comprehensive review.

Charger Connector Review:

The charge reception of the batteries and the ratings of the charger are not only the limiting factors for power delivered to EVs but it is also dependent on the type of connectors as well as shown in Table 2 [22,23]. According to the power output and charging speeds available to EVs the charger connectors are divided into three types slow, fast, and rapid.

Table 2. The types of XFC charger available in the market [22,23].

Shape of Inlet					
Manufacturer	CCS Combo 1	CHAdeMO	CCS Combo 2	GB/T 2D234 DC	Tesla Super Charger
Voltage/Power	600 V/75 kW	500 V/200 kW	1000 V/200 kW	750 V/187.5 kW	480 V/140 kW

Slow chargers are the ones that are the home chargers or level 1 charger which are rated up to 3 kW (16 A). The fast ones are the level 2 rated 7–22 kW (32 A) and are used in public spaces like parking lots of offices etc. [23]. This paper tries to review the ultra-fast charging, so only connectors available for rapid charging will be reviewed. CHAdeMO or CCS charging standards are used by rapid DC chargers providing power at 50 kW (125 A) [24]. An EV is charged to 80% in 20 min by both the chargers contingent upon the battery capacity and initial SoC. 100 kW or more rates are provided by Ultra-Rapid DC chargers. Typical rates being, 100 kW, 150 kW, or 350 kW, although the battery can charge in other maximum speeds between these numbers [19,20].

However, the increasing battery capacity of newer EVs are helpful in providing a low charging time with the help from these upcoming models of rapid chargers.

The Supercharger network provided by Tesla, provides rapid DC charging to Tesla drivers via a Tesla Type 2 connector or a Tesla CCS connector based on the model. A 150kW charge rate is possible using these connectors.

Power Electronics:

The power electronics circuitry for XFC stations can broadly be classified into two categories [25–36]. AC to DC and DC to DC.

6.1. AC/DC Rectifier Stage

Most XFC charging stations are AC as the conversion technology is more reliable and tested. The prevalence of AC grid is another reason. As of February 2021, 23,277 number strong Supercharger network is deployed by Tesla with an average of 9 chargers per station. North America has 1101 stations, 592 and 498 in Europe and Asia respectively. All of them being AC/DC stations [6]. Literatures suggest that there is an array of topologies for rectifiers for AC to DC conversion. However, while designing the charging station, several factors are to be considered. The voltage level, the number of ports, the bidirectional power sharing etc. As mentioned before, the AC to DC technology being a prevalent one, many experimental technologies are used, but the success of those is not exactly guaranteed. Therefore, the Pulse Width Modulation (PWM) rectifier and Neutral point clamped rectifier are the tested and dominant technology [30].

6.1.1. Three Phase PWM Rectifiers

The diode bridge rectifiers are cost effective, robust, and easy to install but the operation is not quite smooth. The diode bridge is high in terms of loss. The three-phase bidirectional PWM rectifiers were introduced [30] to solve the problems that the diode bridge rectifiers had, like the high input current harmonics that absorb reactive power from grid. Consequently, only transfer of power from grid to load happens the in case of diode bridge rectifiers as the input power factor becomes small. Low THD, sinusoidal network current and unity power factor are the key advantages of three phase PWM rectifier. Three-phase PWM rectifier charges the battery when in rectifier mode. As demonstrated in Figure 3 [30], in inverter mode, power is transferred to the grid by the three-phase PWM rectifier.

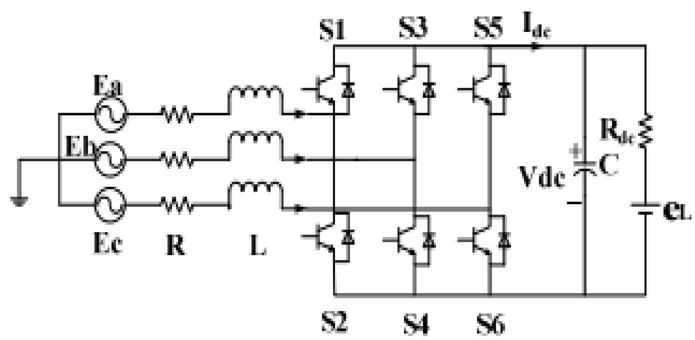


Figure 3 A three phase PWM rectifier [30].

Figure 3 shows the topology of three phase PWM rectifier, which is composed of three phase inductance, three-phase IGBT bridge, the capacitor, and the DC load. With a voltage balanced three-phase input, the PWM rectifier is equivalent to a single-phase circuit. The four-quadrant operation of PWM inverter is as follows, the PWM rectifier only absorbs inductive reactive power from the grid on quadrant 1. It operates to achieve a unity power factor rectifier control on second quadrant. The rectifier absorbs capacitive reactive power from the power grid on the third quadrant. On the fourth quadrant, it can achieve unity power factor active inverter control. Its bi-directional power flow capacity makes it appropriate for charging stations as it ensures a complete V2G operation.

6.1.2. Neutral Point Clamped Converter

Neutral Point Clamped (NPC) converters are constructed of 12 IGBTs and six parallel diodes. As the name suggests, the neutral points of the converter legs, each consisting of four IGBTs and two parallel diodes, are connected in neutral point clamped converter. Higher three-phase grid power quality, low total harmonic distortion (THD), reduced switching frequency, High voltage (HV) and medium voltage (MV) operation, smaller transformer ratio and scalability etc., are the key attractive features for the adaptation of NPC converters in charging stations.

The addition of a voltage balancing circuit proves useful in this regard. A three phase three level neutral point clamped converter [36] is illustrated in Figure 4 [36].

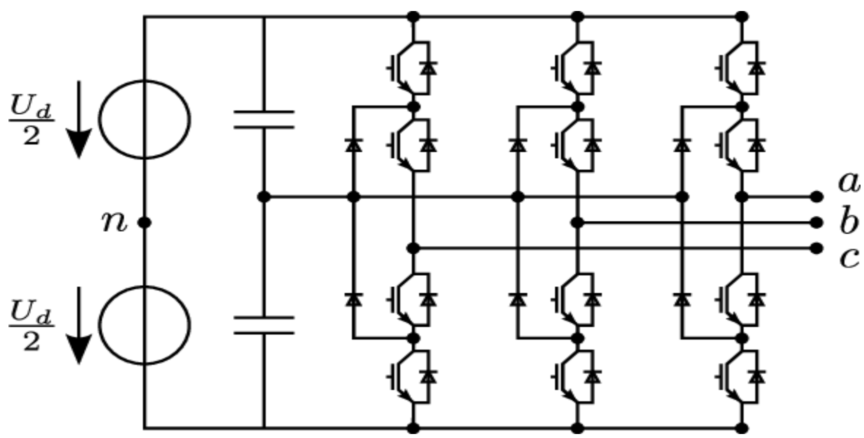


Figure 4: A three phase three level neutral point clamped converter [36].

With the addition of a balancing leg, neutral point clamped converter can also serve as an interface to the bidirectional DC bus in a DC grid making it useful in both MVAC grid and DC grid applications. The lower ripple in the output current and reduced output voltage transient will reduce the filtering and isolation equipment, thus reducing losses. As DC voltage has only two phases, the serial connection of DC capacitor is easily supported without any additional circuit for leakage current compensation. Table 3 presents a comparative view of two and three level PE converters for charging applications.

Table 2 Pros and Cons of Inverter Architecture

Topic	2 Level PWM	3 Level NPC
THD of output current	High	Very low
Stress on active and passive devices	High	Low
Power Density	Low	High
Bidirectional	Yes	Yes
Conduction Loss	Low	High
Switching Loss	High	Low
Efficiency	Low	Very high
Cost	Low	High
Control	Easy	Mid
Input inductor size	Large	Low
Thermal management	Easy	Difficult

A few other lesser used topologies are also highlighted in this section. To attain a higher power factor and lower harmonic distortion, Vienna rectifiers are an efficient but lesser used concept. Figure 5 [37] shows the architecture of Vienna rectifier. Only one active switch per phase makes this topology easier to control.

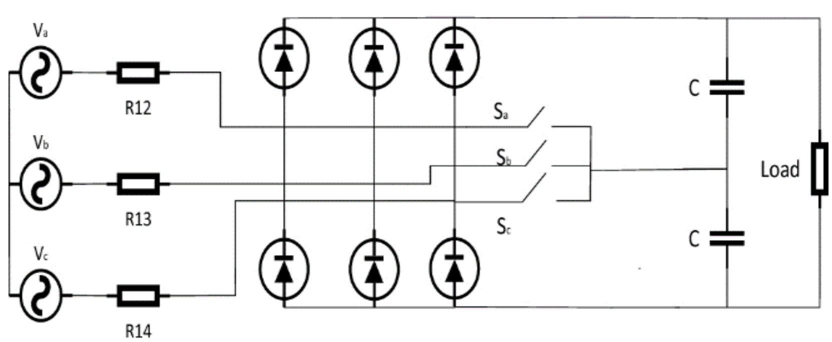


Figure 5 Vienna Rectifier [37].

It is in a way a PWM converter with the boost inductor playing a meaningful role to correct power factor. Whenever the switch is ON, the energy is stored in inductors and transmitted to diodes when OFF [37]. The absence of neutral point makes the switching control easier as no neutral point current problem exists.

As shown in Figure 6 [37], the matrix converter uses an array of bidirectional switches which allow high frequency operation. Although it can improve power factor and reduce the harmonics in line current, the implementation of too many switches makes it impractical to use in charging scenario.

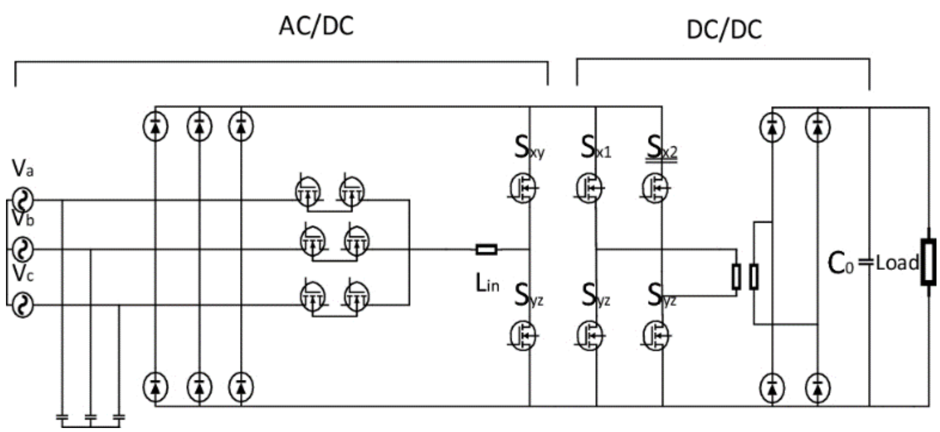


Figure 6 Matrix Converter [37].

Among all the topologies mentioned in this paper, level 3 NPC is the most viable topology to use in XFC. It has a robust structure, low THD of output current and the size of inductor is small. Although it has the problem of neutral point current balancing, that can be averted by programming the correct sequence of switching using a finite control set model predictive control. Upcoming research in this area is promising.

6.2. DC/DC Converter Stage

HVDC and DC is a quickly evolving technology. The one advantage of DC is the choice of one single interconnection to the utility through the front end central. This increases the load diversification. Load diversification leads to different levels of charging schedule corresponding to the state of charge (SoC) of the battery. This leads to lesser cost of converters which reduces the system installation cost. The nonexistence of reactive power in DC systems make easier control technique. Easier islanding is possible due to one single interconnection to the main grid. The opportunity to process partial power thus reducing the system loss and converter cost is another main advantage of DC distribution system [38–50].

The challenges of DC-DC conversion lie in the production of hundreds of amperes of current because the converter is low voltage and high power typically 400 V DC or less. These large currents have several disadvantages including thermal stresses on active and passive components which reduces the efficiency and longevity of the components. Plus, EMI emissions make the packaging technology harder, making the converters large and overpriced. Thus, an efficient, compact, and cost-effective DC-DC converter design is need-ed.

The DC microgrid must interface with several components viz multiple DC-DC chargers, Renewable Energy System (RES) and energy storage while providing grid stability and rapid charging. The main topologies of DC-DC charging can be subdivided into non-isolated and isolated DC-DC converters as discussed below.

The basic difference of non-isolated converter topology is the placement of a capacitor in the input DC side and on the output DC link. When output to input voltage ratio (Vo/Vin) is lower than one, the converter works in discharging mode and in charging mode for vice versa. In case of DAB converters, they deliver power regardless of input output ratio.

6.2.1. Non-Isolated DC-DC Converter

There are three potential non-isolated DC-DC power electronic interfaces topologies which are used in EV power management systems. The half bridge, the SEPIC and the Cuk converter [38]. The half bridge converter has one leg connected with the LC circuit, and the SEPIC converter has an extra leg in boost converter with LC circuit. The Cuk converter replaces that with a freewheeling diode. As this paper tries to focus on XFC charging, only half bridge converter is worth discussing here.

There are several pros and cons of each converter over the other, making them application specific [40]. The half bridge converter has one inductor, so the losses are far low. Due to lower inductor conduction and lower switching and conduction losses on active components half bridge has higher efficiencies. The energy handling requirement and the core plus conduction loss is almost like Cuk and SEPIC converter.

The main disadvantage of the half bridge converter when operating as a boost converter is the discontinuous output current which affects the function of the output capacitor. After reviewing three types of non-isolated DC-DC converters [42–44], the half bridge can be recommended as the most efficient for XFC operation. A half bridge converter can be seen in the Figure 7 [43].

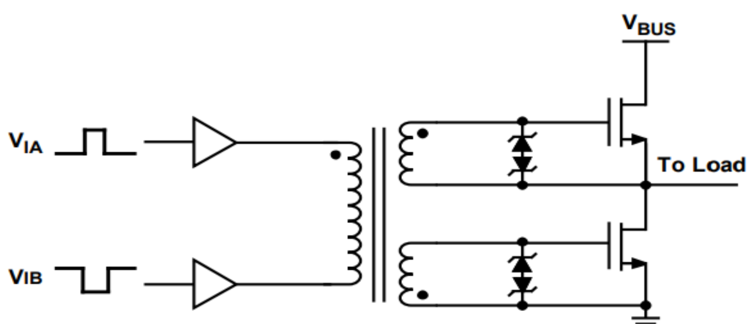


Figure 7 . Non isolated DC-DC architecture—Half bridge [43].

6.2.2. Isolated DC-DC Converter

High power isolated bi-directional DC-DC converters are most used converters as they provide galvanic isolation, V2G capability and have a reduced carbon footprint on the environment, as well as being cost-effective [45]. There are different topologies of isolated DC-DC converters operating in many areas. Full bridge, half bridge, push-pull, to name a few.

However, the charging stations need a converter that is compact and has high power handling capability. Therefore, the LLC, and DAB converters are primarily used for this application.

LLC converter:

The LLC converter uses a high frequency transformer instead of a high frequency capacitor. This increases battery life [43–46]. The criteria for choosing the converter topology include high reliability, efficiency, and low cost. Figure 8 shows the schematic for an LLC converter for XFC application.

LLC converters are also in widespread use for its high efficiency at resonant frequency and its ability to regulate the output voltage during the hold-up time in telecom industry. The output voltage is constant, but a significant drop in input voltage might be noticed in a short time. Fuel cell applications also use these converters.

A prototype converter in [45] that has been designed with switching frequencies of 50 kHz in the boost stage and 300 kHz in the LLC stage, it gives experimental results of efficiency more than 90.2%.

LLC converter have added advantages like the efficiency is superior at low and medium load because the switching loss is little. This converter is useful in bidirectional applications because it has a bidirectional power flow in regards to the input and output conditions. This is what is essential for V2G applications. An isolated LLC converter [46] is shown in Figure 8.

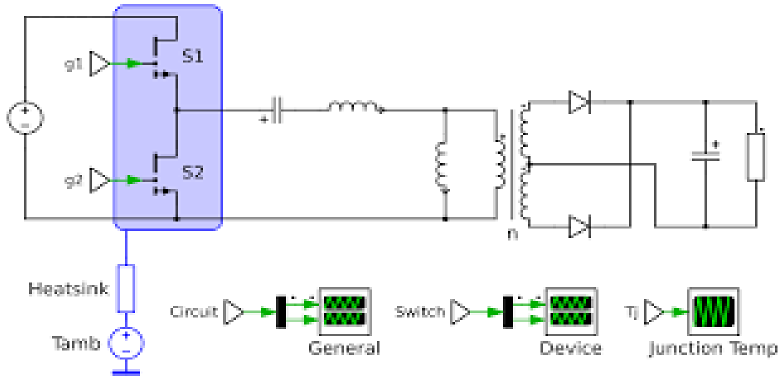


Figure 8 . An isolated LLC converter for charging station applications [46].

Dual Active Bridge Converter:

A symmetrical circuit topology is used in dual active bridge converters (DAB) where two voltage source converters are inserted on top and bottom of a high frequency transformer with a unity turns ratio. The DC-DC converter is characterized by the less switching losses on diodes and less ripple voltage/current stress on the two dc capacitors. The DAB converter is capable of zero voltage switching making it applicable in a wide range of power ratings depending on the available power device's switching frequency [46]. A Dual Active Bridge converter is illustrated in Figure 9[4]. However, their conversion efficiency is not commendable at high-frequency operations [24].

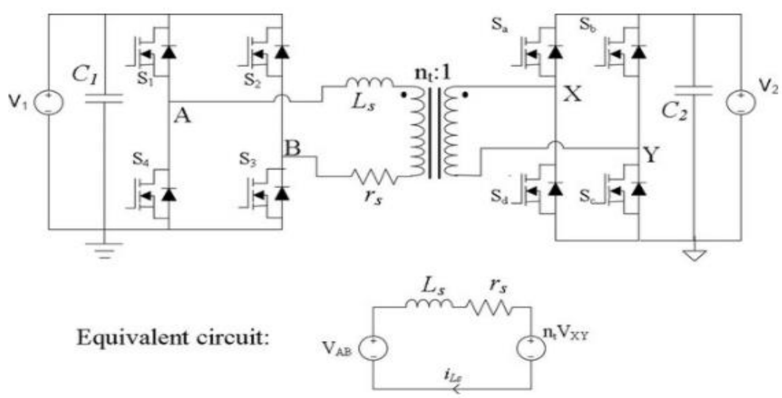


Figure 9. A Dual Active Bridge Converter for Charging Stations [48].

Series and/or parallel connections of multiple DAB dc-dc converters would make it easy to expand the voltage and/or current ratings such as the converters were operating as a single high-power DAB DC-DC converter.

They can also perform well with added ESU technology [49]. In particular, the input series and output-parallel connections show considerable promise as a DC-DC converter for medium-voltage high power battery energy storage systems and an interface circuit between two DC power networks with different DC voltages.

When the next generation SiC-MOSFET modules come across, the conversion efficiency of a well-designed DAB DC-DC converter is expected to be higher than 98% in a wide range of power ratings.

The power electronics topology selection not only depends on simple facts like, the output power rating or maintaining grid stability by frequency control, but also on the voltage to grid reactive power operation, the interfacing of electric vehicles and the impact on energy storage units etc. However, power electronics is a very competitive field and there are a multitude of topologies in research and development stage, the topologies discussed in this section have been investigated keeping these aforementioned factors in mind. The comparative analysis of the DC/DC topologies can be found in table 4 below.

Table 3 Pros and Cons of isolated DC/DC topologies [32–42].

Type	**LLC Converter**	**Dual Active Bridge**
Device stress	Higher	High
Transformer Rating	High	Low
Input and Output capacitor current	High	Low
Operation	Bidirectional	Bidirectional
Conduction Losses	High	Lowest
Turn ON switching loss	ZVS	ZVS
Turn OFF switching loss	Low	High
Total losses	Low	Medium
Control Complexity	Moderate	Simple to complex

Wide battery voltage, fixed bus voltage	No	Yes
Paralleling modules	Intensive	Easy
Switching frequency	Fixed/high (Si/Sic)	High

DC Fast Charging (DCFC) Station Cost Analysis:

Investing in DCFC as a promising technology might be tricky as the high voltage generation, operation and equipment have high costs. The ways to mitigate these are discussed in the several section of this paper. Nonetheless, a look into the cost of operation of a DC-XFC is analyzed in this section. Utility demand charges based on highest monthly peak power drawn by the customers, including charging stations. This is done to recoup the fixed cost of generation, transmission, and distribution [12]. According to 2020 tariff data, demand charges can range from 2–90 USD/kW [5]. To put the cost-efficient model into perspective, a practical case needs to be examined. Tesla recently installed 56 numbers of V3 supercharger in a charging station in CA, making it the largest charging station by them to date [4]. The convenient location near a store and restaurant makes planners think that it will be utilized enough to gain profit. Most of the charging stations are not utilized more than 12–18% of its capacity but power calculation of such a charging station is done at 100% occupancy for 24 h a day for cost analysis purposes [38]. The 250kW charger being utilized 24 h a day for 365 days will need 2190 MWh of power. The on peak times can be given as 12 PM to 7 PM during the summer months of high temperature and 8 AM to 3 PM during the colder months. The average per unit cost of electricity in California is 16.67 cents/kWh [5]. Depending on the location and the tiers decided by PG&E the price of electricity can be 30 to 50 cents in peak hours. Thus, for 2190 MWh power the cost of the peak hour electricity becomes

191,625 $USD/year for 30 cents/kWh or 319,375 USD/year at 50 cents/kWh, for 7 h a day, 365 days [51].

However, solar energy costs from 6 cents/kWh to 10 cents/kWh [51]. Replacing the grid power with solar generated power, the charge per day, for 7 h, will be 63,875 USD/year or 38,325 USD/year for 7 h a day, for 365 days, for prices 10 C/kWh and 6 cents/kWh, respectively. Thus, giving savings from 153,300 USD to 255,500 USD per year for different rate and tariff types [51]. A similar approach replacing solar with energy storage system (ESS) is discussed in [12]. The capital cost of Solar Energy station might be paid off in a year or two with the savings made in tariff [12]. The example of California cited in this section represent a large number of global populations. In Europe and certain parts of Asia, the incident solar intensity is lower than that of California. However, the cost of electric power in these parts of the world is much higher than that of California. Thus, even with lower intensity, the cost of electric power generated by solar will be lower than that of conventional grid. There are some parts of the world where solar intensity is very low, but in these places lower cost wind generated green electric power is available.

Impact on Sustainability

Sustainability plays a big role in today's scientific world. With the spread of internet and social media, people have greater access to knowledge which has opened their eyes to a countless variety of issues, and global warming is one of the major ones. This climate is for the humanity to preserve and in order to do so, the first step is to reduce pollution. The number of pollutants releasing factors are many but can be broadly classified into three types, viz vehicle emission, industrial emission, and personal usage emission. The vehicle emission can be easily reduced with the widespread usage of EV.

The charging station is useful in this interest to make the EVs functional. It is up to the general customer to adopt EVs and the utility grid to inject more renewables into grid so that the energy EV draws is clean [52]-[68]. But fast charging stations are rarely found at home. It is either set up by the EV manufacturing company or by any corporation for their employees from any individual charging station manufacturers like ChargePoint or Wall box [55]. Therefore, company policies and the ethical sourcing of energy for on campus charging will play a big role in shaping the future of sustainability for XFC.

The Protection of EVCS:

An understanding of charging station configuration and its fault behaviors is important to develop a comprehensive protection system. This section sheds light on the charging station protection architecture and the rooms for improvement. Tesla has recently opened a 250 KW, with 56 chargers in a charging station [51]-[54]. A charging station is basically a small HVDC system. That means the protection architecture is quite similar [61]. The power architecture of charging station is shown below.

Most of the charging stations are connected to the AC grid. Although a fully DC grid will be the future of power system but currently the scenario is fully AC with some charging stations doing 100% renewable penetration. The grid connected charging station also provides support to the grid thus carrying a bidirectional power flow. In a nutshell the charging station has two main functions which are fast charging of EVs and Grid conditioning capability. Fast EV charging station can work as a shunt active device to achieve harmonic filtering, reactive power compensation and imbalance compensation with grid conditioning capability [63].

Figure 10 shows high power galvanically isolated inverter converts the grid AC power inro DC. The DC bus should be equipped with ultracapacitors for ripple power filtering and temporary energy storage. High energy losses occur in this power architecture. The EV batteries get charged through the DC/DC converters between the DC bus and EVs. Thus, the charging station protection architecture itself is DC/DC protection.

Figure 10 Figure 10. Power architecture of AC EVCS.

The types of possible faults in the charging station needs to be discussed in a similar way as the HVDC transmission system [55]. In all reality the charging station is a nano HVDC grid with all its functionalities. The types of faults detected in an HVDC system are overcurrent, overvoltage, line to line and line to ground faults. The HVDC equipment have limited fault tolerance ratings compared to AC equipment. DC technology is coming off age and the limitations of DC protection will be discussed in the later parts of this section [64]. The types of DC faults that might occur in an HV fast charging station are as follows:

9.1. Line to Ground Fault

Line to ground fault occurs when the positive and negative lines are shorted to the ground. Faults may occur in overhead lines when lightning strikes the line [54]. That might cause the line to tear, break and touch the ground creating a dangerous fault. In a situation like this where the external system is heavily disrupted, the fault is permanent in nature and the protection devices are obsolete. The only way to repair a heavily impaired line to ground fault is to isolate the line and repair with the help of technicians. Other than lightning, storms or any external forces which might cause the trees to fall on the line may also cause line to ground fault. Sometimes it is caused by a small object, and it can be restored once the disturbing object is removed without causing much disruption. The line must be taken out of service until the fault path is cleared. In theory, underground cables or encased systems like charging stations are completely protected from line to ground faults. However, they still can occur due to improper installment of the casing, breaking of the system by external force or attempt to theft of charging station equipment or many such things. When this happens the broken cable insulation will provide a path for line to ground fault. In either case this will require a complete shutdown of the station and costly repair. The line to ground fault rapidly discharges the capacitor to ground from the faulted pole end. This causes a phase imbalance creating high currents that might damage the capacitors and power electronic converters in the system.

9.2. Line to Line Fault

The occurrence of line-to-line fault in an enclosed environment like the EVSE is rare. The failure of switching devices might cause the lines to short [62]. The switching fault is independent of the converter connection or rating. It might cause the positive and negative bus to short in the encasement that could generate a fault that is mostly temporary.

9.3. Overcurrent

Both kinds of faults mentioned earlier might be subjected to overcurrent fault if the appropriate protection is not there [62]. In other times, an overcurrent fault might occur when the system is overloaded. The two terminal systems are subjected to overcurrent fault in case the converter is overloaded because of the fault in another part of the system. For instance, if multiple converters are engaged in a series or parallel connection to generate the high-power ratings needed for the fast-charging stations. If one converter fails, then the others will be overloaded thus generating overcurrent in the system. Thus, the protection devices should intelligently drop the faulty line and create a shunt resistance path to avoid damage of the remaining converters. More on this will be discussed in the equipment subsection. When similar fault happens in power grids, black out is the smartest thing to do to avoid spread of the fault throughout the network.

9.4. Overvoltage

The types of protection devices are two. AC and DC. AC devices are installed at the grid to charging station interface which isolates the charging station in case of a fault in the network. DC devices are installed inside the charging station to regulate the system in case of the aforementioned faults that might harm the entire set of equipment building the individual charging station or the network of charging stations in a facility. The devices used for these both kinds of protection are elaborated below [63,64].

9.5. AC circuit Breakers

For cost effectiveness the charging station node can be easily protected by an AC circuit breaker. It is readily available and replaceable. But AC circuit breakers have mechanical parts that take long time to repair. The charge of DC capacitors will be monitored back to the standard relay that observes over/under voltage/current. At the onset of fault, capacitors will discharge causing the voltage to decrease and the current will increase over the rated value. Once the relay senses the anomaly, it will trip the circuit breaker protecting the charging station network.

9.6. DC Protection

The rest of the charging station utilizes DC protection in form of fast acting solid state circuit breakers and switches [64]. The monitored voltage and current through each line will send the necessary signals to the respective solid-state device. The fast-acting DC switch will open once the fault is detected. This type of fault can be cleared without interrupting the entire network as each line has its own solid-state device. This type of mechanism is also more expensive due to the presence of switches in all the lines. Furthermore, if the device is placed in a positive line, it cannot detect the fault in negative like other switches. DC protection devices also protect against overvoltage by implementing a chop-per circuit.

Solid state circuit breakers (SSCB) are quickly emerging technology that suits well with high efficiency DC applications like fast charging stations. Fault clearing operation needs to be faster, and the advanced semiconductor technology is helpful in this regard. The increased research in the material and topology of semiconductor devices has stimulated an increased development in SSCB. Wide Band Gap (WBG) devices are used in SSCB, which have robust material properties that make their operation at higher temperature, voltage and switching speed easier. Their low conduction losses per specific die area are also worth mentioning. For this reason, authors suggest that a substantial amount of WBG research should be redirected at SSCB applications.

Reliability

The reliability estimation of EV fast charging system is another aspect to consider be-fore proceeding. A thorough reliability estimation model must be developed to ensure a robust fast charging infrastructure.

First the voltage, current, and thermal stresses on semiconductor switches must be analyzed based on a mission profile through a comprehensive mathematical and simulation model. It should propose the lifetime prediction and the reliability analysis from the data provided by thermal stress. Thus, this information can be used in a notional fast charging system planning to ensure a long life of operation [65].

More on this has been discussed in the cyber security and discussion section. The impact of implementation of AI in a reliable and secure charging network remains an area of interest and those sections shed ample light on it.

11. Cyber Security for XFC

Electric vehicle charging stations will become a part of the national critical infrastructure and, therefore, a target for attack. It will be a part of both the transportation and financial infrastructure.

This will make it attractive to numerous types of attackers [66]. The modified attack taxonomy on automobile security can be found in Figure 11 [67].

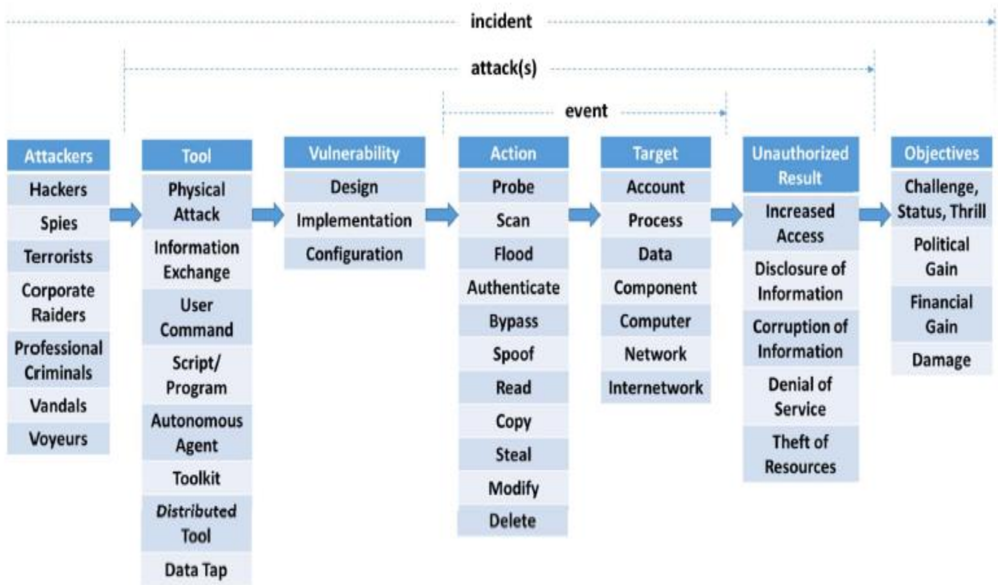


Figure 11 Modified attack taxonomy for Power System threatening the charging network [67].

In addition to the typical attack sources, it should be noted that electric vehicles pre-sent a threat to some very well-resourced adversaries. It is a revenue threat for gasoline producing countries including but not limited to, Russia, Iran, and Saudi Arabia. Attackers from those countries will be strongly motivated to attack charging networks and make Electrification of Transportation (EOT) unattractive. For some of these countries, it is often unclear whether the attacks are only criminal, or state sanctioned. Groups associated with Iran have already attacked computers associated with Saudi oil production [68] showing both their willingness and ability to attack critical infrastructure to safeguard their petroleum revenue stream. This should not be surprising, since US officials planned in the past to destroy Iranian power infrastructure [69]. Russian entities are frequently the source of computer security incidents and attacks on critical infrastructure. However, it is often difficult to say if these attacks are purely criminal, sanctioned by one of the many intelligence services involved in network hacking (GRU, SVR, FSB, etc.), or some combination of the two.

A ransomware attack initiated by Russian hackers shut down everything from supermarkets in Sweden to kindergartens in New Zealand earlier this July 2021[70]. This included the gasoline pipeline supplying the US East Coast. It is worth noting, that the weaponized software behind most Russian software was originally developed by the NSA and used by the Russians only after compromising NSA internal security. This was established by Israeli operations that compromised GRU internal security [71]. These incidents illustrate the vulnerability of US critical infrastructure to compromise by well-resourced opponents.

The connections of charging infrastructure to automobiles are particularly concerning, due to the relatively poor security of automotive systems. In general, automobiles have multiple ECUs communicating over the internal CAN Bus. The CAN Bus has notorious security problems. Devices are not authenticated. Communications are in clear text. All messages are easy to spoof. This means that if any ECU is compromised all vehicle functionality is at risk. Originally, it was assumed that the automobile would be a closed system. Unfortunately, later developments allow EV communication bus to be accessed via numerous wireless network technologies. To start the protection, charging stations should assume the vehicle they connect to is compromised and insecure. They will need to assure end-to-end security by having communications endpoints in the car be hardened and tamper-proof. These end devices need to authenticate themselves using a separate public cryptography secret key for each automobile. It would be advisable to have these devices be inside a faraday cage, have their own internal power supply, and delete the authentication key, should the faraday cage be compromised. Heat sensors that verify that the device temperature never goes beneath a specific value is also worthwhile to avoid forensic memory analysis by leveraging a well-known but rarely used variant of the evil maid at-tack [71][72].

Several times in the past decade Chinese cybercriminals have breached the cloud and taken valuable information for using against the US government [73]. This is often related to supply chain attacks. Current software practice uses software from other vendors to construct new systems. Unfortunately, if the up-stream supplier has been compromised, then all security guarantees are off. Research is sorely needed to find ways of isolating the security implications of software component use and re-use. This will require a clean-slate redesign of software development and integration models.

To alleviate this problem, apart from imposing strong regulations to data acquisition and software terms and agreements, another approach might be to change the power system network completely to DC power. In addition to capital cost, and power savings, DC networks, have desirable characteristics for cyber security. Mainly, individual networks are isolated from the global system. Sandworm APT's attack on Ukraine [74] would not have been possible in a local network of DC power. A local DC network should be able to stop cascading failures. Non-intentional disruptions would easily be isolated and contained but isolating intentional disruptions would still be hard. For example, ransomware could still disable individual DC networks, but the reach of the attack would be limited. Decentralizing control of the grid would force attackers to compromise many control centers that are independently maintained. Attacking the individual DC power network is al-so less attractive since disabling isolated neighborhoods is less useful than disabling a whole country. A major issue is defining standardized local power networks. Clear standards and well analyzed software will help to create secure systems. This is countered by the legitimate concern that monocultures where many systems run identical software are riskier. Once a vulnerability is found, the whole grid is immediately compromised. Decentralization has risks, too. When many systems are individually installed, configured, and maintained, the risk of components being incompetently maintained grows exponentially. The decentralization of the Local DC power networks architecture has desirable characteristics as well as risks. However, for nation-state attackers, note that the amount of effort that is currently being used to disable an entire country would only disable a single house, or neighborhood. While wide-spread attacks would be possible in theory, they would most likely no longer be financially attractive for foreign governments.

11.1. Threats in Charging Network during Billing

Some potential threats are discussed below that encourages the integration of security measures in charging infrastructure right from the beginning. The threats range from vehicle connection to communication and specifics of vehicle charging.

A passive attack that might gain personal information or more for additional attacks by intercepting information. A physical or logical access to the communication connection is required to the adversary [75,76]. Both charging station to car and charging station to grid communication can be intercepted as shown in Figure 12 [75] below.

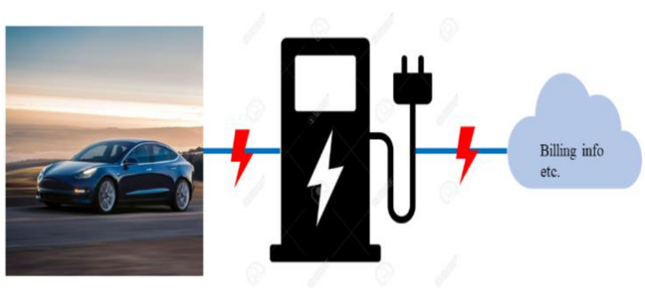


Figure 12 Interception of information via charging stations [75].

The loophole in the system begins when the radiation of the communication transfer to the adversary when the physical or logical access to the communication connection is in closer vicinity to the communication rather than having direct physical address. Power line communication of

PLC is one such technology that comes to mind. As shown in the figure above the valuable information that can be stolen ranges from tariff data, billing info or charging status. For billing, it is a solved problem with two solutions: credit card companies or cryptocurrency. Credit card companies solve the problem largely by using lawyers. The problem is that users lose individual control and privacy. Crypto currency is an attractive alternative but can make law enforcement more difficult and current versions are bad for the environment.

11.1.1. Man-in-the-Middle-Attack

This refers to the attack that consists of the modification of the information intercepted from the vehicle and supplying to the vehicle or grid to mess up the synchronous operation. This refers to the attack that consists of the modification of the information intercepted from the vehicle and supplying to the vehicle or grid to mess up the synchronous operation. [76–78] Such as the case of charging spot being provided wrong tariff information by the adversary. It is easily accomplished by a modified charging cable. It can be visualized in the Figure 13 [79].

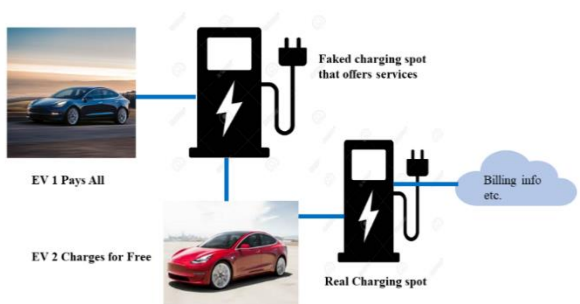


Figure 13 Man in the middle attack [79].

As shown in the Figure 13 above another scenario is the usage of a fake charging spot in between the real spot and the vehicle. Thus, the customer connects to the fake spot and thus their assets get stolen. The customer does not get any hint because the fake charging spot is connected to a communication router to a real charging spot. Another threat is the theft of energy while the customer is charging the vehicle, a fraction of the total energy only gets to the vehicle, and rest gets stolen by the fake spot while the customer pays the full price of the energy.

Another facet of this kind of theft is that the adversary manipulates the energy path not the communication path, the communication path remains untouched, and the customer doesn't have a clue of the theft. This made the authors strongly suggest research on the dire need of connecting the information flow and the energy path.

11.1.2. Other Types of Threats

Another means is the transaction falsification in which the customer receives extra bill for fake energy by intercepting their information or the utility might charge them extra for modified information that makes them think that the customer used that energy.

The attack might also happen from within the vehicle. The owner might connect to a charging network and inject or modify application level traffic as an attack. Sometimes this might happen to no fault of the owner through malware or faulty software component. Various apps installed in mobile devices which communicate with the car are also a vulnerable node [69].

As the previous point remains valid here, the customer might be the adversary and might use pirated or replacement parts to acquire, modify or control information affecting the charging infrastructure and the EV itself. Several steps including the participation of ethical hackers is required to alleviate the threats in charging network [73].

11.2. Moving Target Based Defense

The battery electric vehicles in the grid increase the power capacity and networking requirements and create a threat in the charging system. Therefore, the increase in adversarial attack calls for security measures to be taken in the involved cyber physical system. The battery management system (BMS) is the first line of defense against cyberattacks, as the battery is the first line of contact between the grid and the vehicle. A compromised vehicle may contaminate the entire charging network. Therefore, the BMS security is imperative. A moving target defense (MTD) based novel approach must be implemented for the security of the vehicle BMS [79]. In literature there are several studies on the security hardened BMS which aims to increase the security and performance of operations between the charging station, the BMS, and the battery system of electric vehicles has been hypothesized [69,75,79]. The redundancies of the controller and feedback design are used in MTD based switching strategy. The acceptable charging performance under attack might be studied from the simulations that model the degree of unpredictability.

To take this MTD based study a notch farther, the security against the adversarial attacks, known as spoofing and replay of CAN bus should be implemented. A charge control strategy is developed for the redundant BMS controllers and observers, which gives promising results without the large calculations of authentication methods. This can be implemented practically for XFC and other CPS and IOT applications under attack.

The threats in charging network are summarized in Table 5.

Table 4 The Threats in Charging Network.

Attackers	**Target**	**Type of Attack**	**Result**
Spies	Charging Network	Passive	Stolen Financial Information
Corporate Hackers	EV	Active	Overcharging the owner
Professional Cyber Criminal	Billing info	Passive	Large bill

11.3. Other Mitigation Techniques

Air gapped network, anomaly detection approaches, big pipes, and traffic filtering etc. are few network security techniques to reduce power Systems cyberattacks [67]. A security technique called air gapped network isolates the vulnerable network from rest of the secured power system. A similar technique can be applied in charging infrastructure where the breached charging point will immediately be cut off from the rest of the station. To take it a notch farther, shutting down the entire car except the battery, so that no communication takes place during charging, might also be a good idea. Anomaly detection approaches are used to detect attacks on power systems networks [64]. However, the detection performance is high if the network is utilized less. Thus, for a big charging infrastructure, this might not be as effective. Network connections viz big pipes with bandwidth that can absorb attack traffic to mitigate the cyberattack on the system are very costly. Traffic filtering is another approach that filters the attack traffic from the normal traffic thus stopping the attack. However, large traffic volume and lack of documentation makes this approach difficult to implement [67]. Other than these technical approaches, strong regulations regarding the data collected by IT companies and the access to that data must be imposed. If there is no financial, legal penalty, industry does not care about customers [80].

For finances, there are two choices, just using credit card companies are a viable option. They have lawyers and know how to find and punish abuser. In addition, they know how to price in losses due to fraud and criminality. Ref. [81]-[83] The use of crypto currencies the buying and selling of them also expose the system to threat [82].

As mentioned above, DC microgrid can be isolated and get rid of most vulnerabilities. Using larger grid has many problems [67] including market manipulation [80]. The national grid is very open to attacks by well-funded opponents, including stolen NSA cyberweapons [69]. Since the cyberweapons leverage security flaws that are classified in the USA, there is no way for industry to guard against it. Many recent attacks are supply chain attacks. This means that any flaw in any software used by anyone in the development process can result in a fatal compromise. There is no way to guard against this. This can also include hardware Trojans, since practically all chips are produced in Asia that are controlled by potential global rivals to the USA, hence there is no practical mitigation [71].

Due to the paradigm shift in connected and autonomous vehicle technologies the automakers are introducing the connected autonomous vehicles with self-driving and self-parking features. Therefore, traffic flow prediction (TFP) using Support Vector Data De-scription (SVDD) model is used to smooth out raw data and enhance filtration points [84] to improve prediction accuracy. Despite using these models to perfect raw data, unexpected scenarios such as extreme weather events or pandemics like COVID-19 might hap-pen. In that case, based on the indoor-outdoor temperature and the subsequent electric power consumption, a data model is generated and developed using TensorFlow framework [85]. A detailed investigation on the electricity consumption and COVID-19 pandemic has been done in reference [86] and a conceptual framework is developed to alleviate the impact of uncertainty in case of extreme scenarios, weather or pandemic alike. Machine learning models with datasets consisting of charging, processed from the workplaces since 2016 to 2018 were gathered in reference [87]. It consisted of a heterogeneous EV fleet of more than 1000 vehicles. After processing through machine learning algorithms, a 21% more charging infrastructure usage was reported [87]. The authors in reference [88] pro-vided a comparative analysis of various supervised, unsupervised, and deep learning methods for EV charging predictions. The findings show that high dimensional datasets were not available due to lack of comprehensive cluster analysis in the charging network. Hence a robust data gathering system implementing AI must be incorporated. The problem of false data injection attack (FDIA) in the BESS operation stage has been discussed in reference [89]. According to the authors of reference [89], different system layers must use applied ML and AI methods for FDIA detection. Methods such as clustering and artificial-neutral-network (ANN) based state estimation forecast are recommended. With enhanced usage of AI in charging network, the power consumption can be regulated, infrastructure can be accurately used, and the security of cyber physical system will be enhanced making EVs attractive to customers.

DC microgrids that are not attached to the global grid are the better solution for security and environmental reasons. Using established credit card infrastructure for payments and following their standards is best. To avoid meaningless death, passing legislations to safeguard the security of consumers is imperative. The cyber threat is a problem that needs sound technical approaches, strong business ethics and stringent government regulations in equal measures, to make charging infrastructure a secure place for consumers.

Transformative Role of Silicon Carbide in DC-Fast Charging

Silicon devices have dominated the world of power electronics in the last several decades in a wide range of power applications. A large amount of energy is dissipated during conversion steps of AC/DC/AC due to the low electrothermal conductivity of silicon devices. High operating electric field, high operating temperature, high switching frequency, high breakdown voltage, and low losses are several attractive features of silicon carbide devices which cannot be achieved in silicon devices. SiC devices need low output capacitance making it appropriate for high voltage applications. Magnetizing parts like transformers, chokes and inductors etc., are also eliminated or reduced in sizes in SiC applications. Packaging density gets higher as external cooling is reduced.

Due to higher thermal conductivity, silicon carbide devices need smaller heat sink and provide higher system reliability. The weight and load of XFC equipment can be reduced using SiC devices [14]. As the need for cooling decreases, and power density increases, it will reduce charging time as well [14], half the time is estimated in charging for the same power level compared to Si devices. The potential for growth of electrification of transportation is promising by using SiC devices for XFC.

Maintenance of XFC:

After establishing a charging infrastructure for fast charging, the maintenance and electricity procurement defense is a key aspect of the charging infrastructure's validity. As mentioned in Section 7, the cost is an important aspect of charging station operation, and the grid has an important role to play in terms of setting up new ESR to help the charging infrastructure accessible to the consumers.

The maintenance cost for charging infrastructure generally includes storing charging cables securely, checking the machineries periodically, and keeping the charging station equipment sanitary. In case of any breakage or accident the chargers may need repairs as well, which might happen intermittently. The warranty prices of manufacturers vary with the type of protection, the particular charging station operator has subscribed for. As applicable to other machinery, the minor repairs might be minimal but repairing an entirely broken charger after the expiration of warranty, might be costly. Hence a strict structure in terms of the responsibility of site host, charging network and installation manager has to be organized before the charging station goes operational. It is estimated that the annual maintenance cost over charging station is around 400 USD per charger per year [90]. Most of the networks like Tesla, ChargePoint, Wallbox, offer a maintenance plan for an additional annual fee. There is free online supercharger support contact provided by Tesla for its entire supercharger network.

Apart from the maintenance costs the pricing structure has important role to play in the maintenance scenario. The common pricing structures used in the United States are by kWh, by session, by length of time, or through a subscription. The most used structures are session and time based. It is illegal in the United States to sell electricity other than a utility company. Although 50% of public charging is free to use the pricing models across different charging network providers vary depending on different issues, such as, members vs nonmembers, pricing according to subscription, host specifics pricing, and pricing on the kilowatt rate of charge.

As mentioned in Section 11, the collection and analysis of charging infrastructure utilization data contributes to a successful charging station management.

An online portal for utilization data is provided by most charging networks. Sometimes third-party analytics software or a separate electric meter are installed by a non-network charging infrastructure to capture utilization data. Utilization data has a serious risk of breach due to the poor cybersecurity measures implemented by the power grid. If handled carefully, utilization data is very useful to track progress towards emissions and energy goals as well as to determine if a certain pricing structure is successful and to evaluate the need for additional charging infrastructure in the area. A successful maintenance strategy for the long-term operation of charging stations is crucial in order to increase EV’s customer base.

Discussion

Early history of electrical grid saw a battle over AC and DC in which, despite Thomas Edison’s best efforts, AC won. AC had the ease of changing voltage levels with transformers and the transmission of electricity seemed easier. But after almost hundred and fifty years later AC power is still predominantly used in grid despite having huge power losses and higher cost.

DC power is energy efficient, reliable, and has a better quality of power. The power density of DC machines is way higher than AC machines. DC also is inherently compatible with free fuel energy (solar and wind) systems generating intermittent DC power stored in batteries to have a reliable power supply. Solar PV is inherently a DC energy supply, as are batteries, making DC a more naturally compatible interface. Any energy storage technology is DC based, creating opportunities for improved integration efficiencies, and reduced operating losses.

Most of the modern electronic equipment like cell phones, laptops, and household appliances are DC. If the requirement for converting energy could be eliminated, then efficiency will increase. Reduced loss will also reduce the dissipated heat in electronic circuitry so that the electronic equipment lasts longer. The technology of DC power in data centers, homes, and communities is making significant advances.

Moreover, different countries operate in different power frequencies and qualities. Due to this, different countries need different conversion equipment which is an additional hassle. If universal DC is accepted, then one single equipment can travel the world. In places like Alaska where human population is scarce, power is generated in a nano grid system and DC is prevalent as it is convenient. In the rural areas of low GDP countries or the war ridden countries which have their power grid destroyed, DC is used. While charging from AC power, whether be it from household 120 V or 240 V outlet or use J1772 charging equipment, the car’s rectifier converts that power to DC. Therefore, there are multiple levels of conversion and associated losses before the power can reach the battery.

From safety and carbon emission point of view, PV generation of electric power is the best technology [91]. The cost of photovoltaics generated electric power is lower than any other energy source [92]. At utility scale, the cost of PV generated electric power has reached as low as 0.0104 USD/kWh [92]. Due to advancement in technology and volume manufacturing, the cost of lithium-ion batteries is falling constantly [93]. For four hours of power storage currently the cost of stored electric power is 0.8 cents/kWh to 1.4 cents/kWh and has the potential to reach to 0.4 cents/kWh to 0.9 cents/kWh by 2022 [94]. For longer hours of battery use the cost is significantly reduced. For a standalone photovoltaics and lithium-ion battery power network, ad stowing PV generated power in batteries for 16–18 h, the cost of electric power is roughly half than the cost current AC grid [94].

As mentioned in the introduction, reference [8] has an extensive review of power electronics topologies but other aspects remain untouched. Every aspect of the shortcomings in engineering for charging station has been thoroughly analyzed in this paper. The authors of reference [8] don't delve into the subject of DC grid or silicon carbide power electronics for fast charging. This paper addresses that as well. In reference [9] emphasis is placed on the charging equipment and inductive charging. The scopes of inductive charging remain doubtful economically for heavy duty vehicles because of their high losses. Therefore, this paper recommends the reduction of losses in power systems by adopting SiC power electronics. In reference [10], the authors discuss all levels of charging, but no special emphasis is given on fast charging, so this paper focuses solely on the XFC architecture. The charging standards are mentioned in [11] but technical aspects are not as deeply investigated as this paper. The energy storage design for DCFC is mentioned in [12] but the important aspects of power electronics, security which are valuable for a good energy storage are not paid attention to, this paper addresses those issues. The emphasis of this review paper is on relevant power electronics technologies of DC fast charging and other aspects such as cyber security, protection, impact of DC power clean electrical power networks and the role of silicon carbide power electronics in fast deployment of XFC on a large-scale basis.

To advance the technology of XFC, advancements must be made both in the power network as well as the XFC. Figure 13 shows our proposed system. If the DC power generated by PV and battery-based power network can be used locally, there is no need of transmission of power. This concept is exactly what Thomas Edison proposed and involve minimum distance between power source and load as well as minimum power conversions [95]. In case of long-haul transmission, HVDC is used and there is opportunity to design and fabricate high voltage solid state silicon carbide converters. The use of larger silicon carbide wafers and the use of single wafer manufacturing has the potential of bringing cost of SiC power electronics at par or lower than silicon power electronics [95]. Based on the isolation techniques it is far more viable to isolate a DC charging station in case of a cyber-attack. Judging by all these advantages of DC over AC, it is safe to presume that extremely fast charging technology will be far more efficient and cheaper if DC grid was adopted.

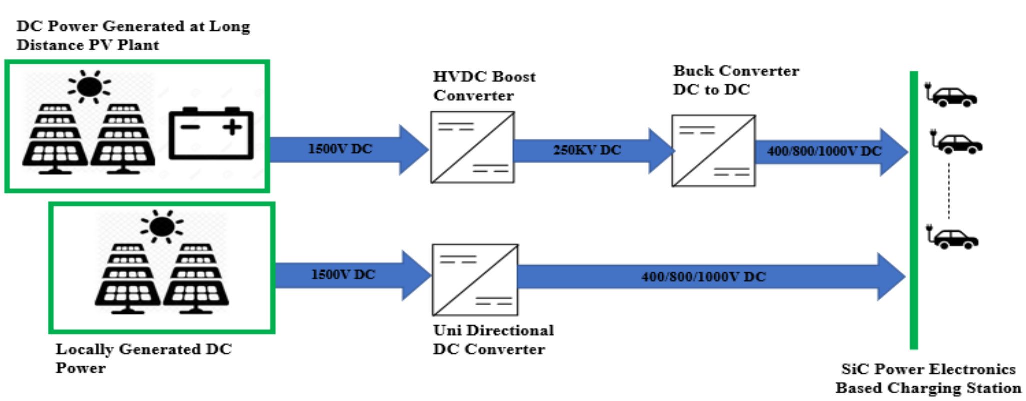


Figure 14 Fully Renewable and DC XFC Charging Infrastructure [14].

Conclusions

Thorough research and planning are required to make a charging infrastructure that will encourage the consumers to opt for EVs for not only daily usage but also for long distance travel and totally forego the ICEV. The power electronics topologies are the cornerstone for charging stations and improving on the current topologies discussed here will make charging stations less expensive, thus more acceptable. The effect of Silicon Carbide in performance improvement of power electronics is discussed. How it effects the environment and what are the cyber threat in the station are also discussed. In this article we have addressed the gaps in research which are hindering the widespread usage of EV in today’s scenario. The technology gaps range from power electronics, protection, DC vs AC to cyber security. Implementing the suggestions proposed here will help reduce power electronics losses, make the protection architecture stronger and secure the network apart from many other aspects. Use of DC power network over AC power can cut down the capital cost of the entire system and provide low-cost charging solution to customers. The acceptance of electric vehicles is not only the individual’s responsibility, but it is a responsibility that lies on government and big corporations alike. This article helps the academia by directing the research initiatives and the industry to develop the necessary architecture to implement the XFC. Modeling a free fuel based fully DC network powered by SiC electronics will form the nucleus of the next step of this research. Although we have emphasized the advantages of DC input power for various loads, practical implementation of DC power as input for XFC as well as for other applications depends on the energy policy of individual country.

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CHAPTER THREE

AN ANALYSIS OF SIC POWER ELECTRONICS IMPLEMENTATION IN GREEN ENERGY BASED EXTREMELY FAST CHARGING

Introduction:

One of the most difficult problems faced by humanity is to solve climate emergency [1]. 24 % of the carbon emission globally is due to transportation as per 2018 data [2]. Among these, road vehicles contribute to 75% of transportation carbon emission [2]. Passenger vehicles contribute to 45.1% of this 75% and the rest come from heavy duty vehicles or freight vehicles [2]. According to 2019 data, 444 million metric tons of carbon dioxide was emitted by medium and heavy-duty trucks contributing to 18% of total global road freight CO2 emission [3]. Thus providing green electric power with highest efficiency of power utilization has the potential of providing solution to greenhouse gas emission due to surface transportation [4][5]. For almost all over the world sustainable electric power can be provided by photovoltaics (PV) and battery-based networks at extremely-low cost, except where solar intensity is less than about 3-4 kWh/m2 per day [6]. In such places wind turbines can be major source of electrical power generation and PV can play the role of supplemental source of electrical power [6]. For automobiles, extremely fast chargers (XFCs) in the power range of 120-350kW are available in the market [2]. Medium/heavy duty trucks can use CharIN MCS charging standard under 1000V/1000A (1MW) today and have potential to use 1500V/3000A (4.5MW) in the future [5]. With advancements in technology and volume manufacturing of lithium-ion batteries, the driving range of new battery electric vehicles (BEVs) has been steadily increasing and BEVs with over 700 miles range are in development stage [7]. However, one of the major roadblocks in the implementation of large-scale electrification of surface transportation is the lack of low cost extremely fast charging (XFC) infrastructure. In a recent article [2] different aspects of current charging infrastructure have been reviewed by the authors and thus they concluded that the power electronics topologies are the cornerstone for charging stations. Creating XFCs more efficiently is the key to making the charging stations low cost and widespread [2]. In this paper improvement in XFC based on DC power and Silicon carbide power electronics has been analyzed. The previously reported literature in this area concentrates in the implementation of Silicon Carbide in EV hence enhancing the EV efficiency, but the implementation of SiC in charging technology remains rarely touched. The novelty of this paper is in the implementation of a new fully DC infrastructure powered by Silicon Carbide power electronics. In a recent review article [2] numerous publications dealing with various aspects of DC-SiC charging infrastructure has been examined by authors, which shows the limitation of previous research in this area. No concrete research is found in the heat loss, charging time reduction or a comparative study between Si or SiC power electronics in EV charging infrastructure. Most of the previous research focuses on the topology selection or particular methodology for heat loss reduction using SiC. A complete system level overview remains untouched in literature. Thus, the objective of this paper is on evaluating a system for XFC, based on end-to-end DC power and Silicon carbide power electronics. Thus providing green electric power with highest efficiency of power utilization has the potential of providing solution to greenhouse gas emission due to surface transportation [4][5]. For almost all over the world sustainable electric power can be provided by photovoltaics (PV) and battery-based network at extremely low cost [8-11], except where solar intensity is less than about 3-4 kWh/m2 per day [6]. In such places wind turbines can be major source of electrical power generation and PV can play the role of supplemental source of electrical power [6].

Importance of DC Power Charging Infrastructure for XFC:

Thomas Edison conceptualized the fundamentals of locally generated DC power thus saving the transmission losses. But since the inception of power transmission, globally the electricity infrastructure is dominated by AC power. The situation is different today. More than 30% of power and capital can be saved by implementing DC instead of current AC based network [12]. Solar photovoltaics generates power in DC form, so does wind energy in erratic AC form that is converted to DC before AC transmission. Batteries and fuel cells store DC power. Due to lower cost of photovoltaics and batteries, high voltage DC (HVDC) transmission is playing a key role in the use of green electric power at the scale of 10.5 GW [13].

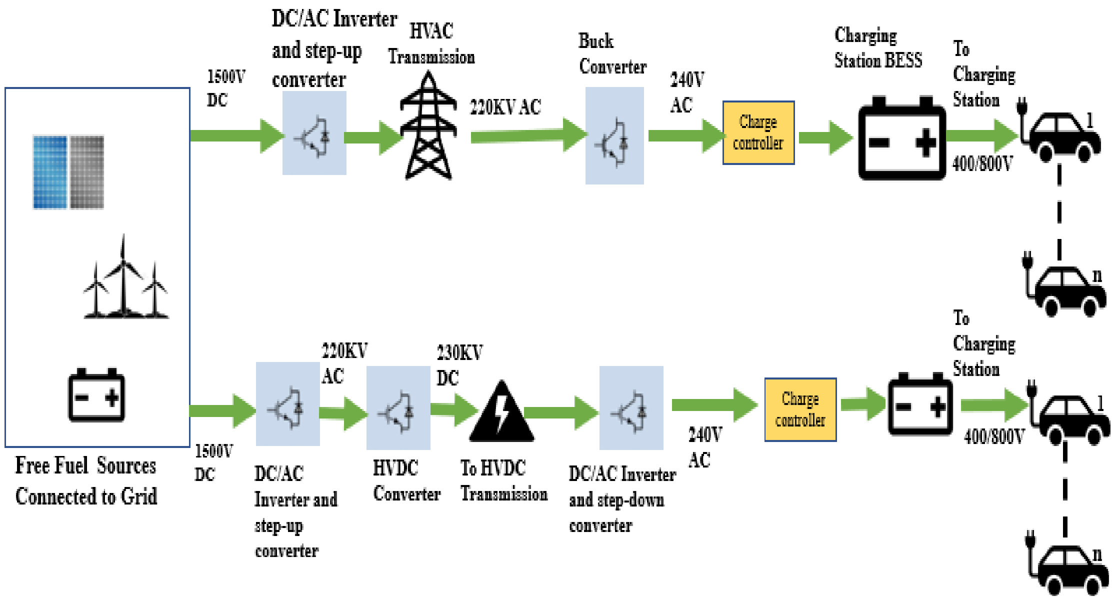

Figure 15: Clean electric power and capital being ruined in current charging infrastructure.

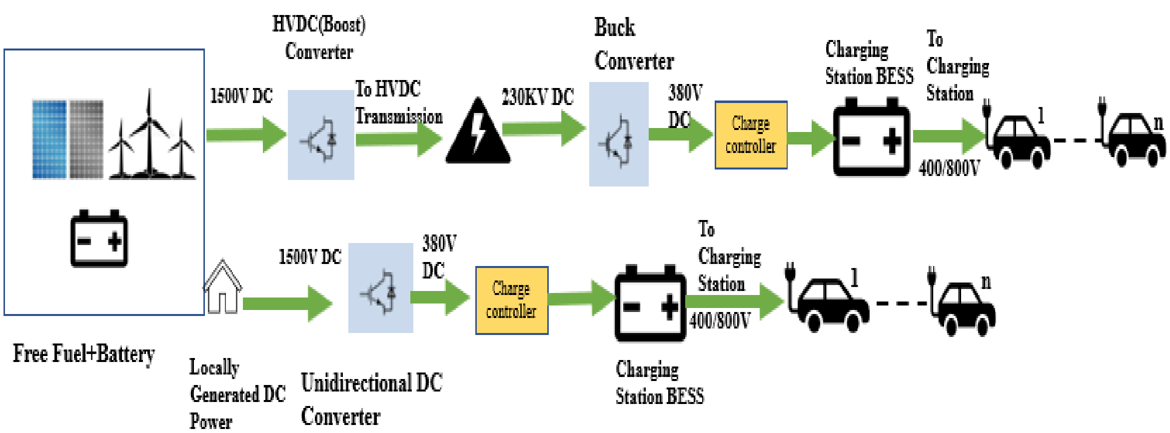

Figure 16 DC power-based charging infrastructure without the necessity of transmission.

As shown in Figure 1, for charging electrical vehicles, the green electrical power generated by solar and or wind and stored in batteries is wasted in several DC to AC and AC to DC conversion steps in current high voltage AC (HVAC) transmission. Even for existing HVDC transmission illustrated in Figure 1, the DC power is first converted to AC power and then converted back to DC power. These unnecessary power conversion steps can be avoided in present day power generation and storage sources.

As depicted in Figure 2, the green DC power is fed to both HVDC network and locally generated LVDC network and feeding the power to charging stations. As compared to Figure 2, the losses in Figure 1 are higher as inverter losses are higher and DC/DC conversion losses are lower to be discussed in the model derived in the next sections.

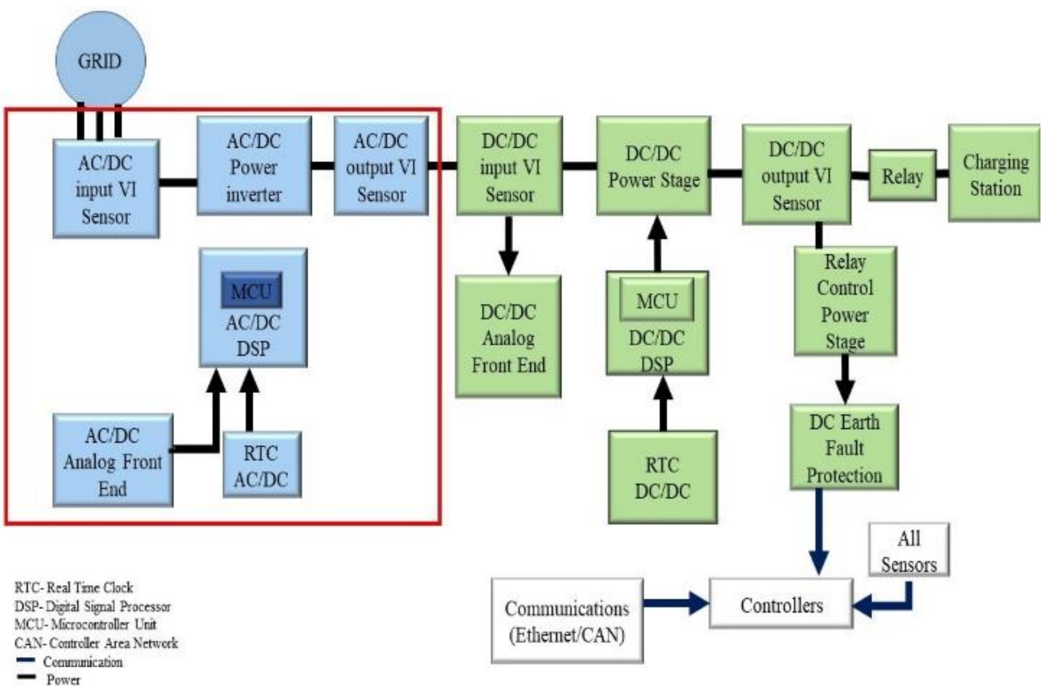

Figure 17 Capital cost savings by lessening equipment and thermal dissipation by electing DC grid. [14]

As depicted in Figure 3, the components shown in blue color, convert AC power into DC power, within current DC fast chargers. Thus wastage of a significant amount of green electrical power and capital is taking place in current charging stations. As opposed to this, if the components used as marked in the blue boxes in the AC system are eliminated, a large amount of electric power and capital can be saved if the entire charging infrastructure is based on DC power.

3. Silicon Carbide Based Power Electronics for Charging Infrastructure

In the last several decades, silicon power devices have dominated the world of power electronics. A large amount of energy is dissipated during conversion steps of AC/DC/AC due to the low electro thermal conductivity of silicon devices. High breakdown voltage, high operating electric field, high operating temperature, high switching frequency and low losses are several compelling advantages of silicon carbide power devices. It is suitable to use SiC devices in high voltage applications with the output capacitance being low. Thus, the magnetizing parts like transformers, chokes and inductors etc. are also reduced in size or eliminated. Packaging density becomes higher as the cooling requirement reduces. The use of SiC power electronics will reduce the dissipated energy, and the device life expectancy will increase due to less thermal exposure. As compared to silicon power electronics cost will be saved in two ways. SiC based power electronics will reduce the losses incurred in EV charging and also reduce the footprint of XFCs. As the cooling need decreases and power density increases, it will also significantly reduce the charging time [15]. By increasing packaging density the voltage capacity of EV can be doubled [16], hence similar technology can also be implemented in charging infrastructure. It also drastically reduces the size of the on board charger as reported in reference [17]. The fundamental limits of silicon power electronics can be overcome by the utilization of silicon carbide ICs in place of silicon ICs. Silicon carbide modules are providing higher power density of motor drive of electric vehicles [18]. Thus by enhancing the performance and cost reduction of power train of EVs and XFC, silicon carbide power electronics has the promise of accelerating growth of electrification of transportation.

4. Model:

In this section the analytical model for power loss calculation has been developed. The calculated values of power loss of Si and SiC devices are compared with the best experimental data available in the literature.

4.1. Methodical Loss Calculation at Device Level:

To calculate the power losses, Si and SiC devices with similar voltage level has been. The Si device is Digi chip N channel MOSFET 2SK2044 [19]. The SiC devices are Infineon F4-11MR12W2M1_B76 [20] and UnitedSiC UF3C170400K3S [21]. Two different SiC MOSFETs are used to show the potential of upcoming technology and will be referred to as SiC 1 and SiC 2 respectively. Infineon F4-11MR12W2M1_B76 is currently being used in high voltage PV and charging applications [14], whereas UnitedSiC is currently being used for Power Factor Correction (PFC) devices and have a potential for charging station applications as well. The parameters from datasheets are given in the Table 1

Table 5 Parameters Used for Calculation

Symbol	Attribute	Si Digichip N channel MOSFET 2SK2044 [19]	SiC Infineon F4-11MR12W2M1_B76[20]	SiC UnitedSiC UF3C170400K3S[21]
I_{DON}	On Time Current	4A	100A	14A

R_{DSON}	On Time Resistance	2.4Ω	14/18mΩ	410mΩ
t_r	Rise Time	15nS	20nS	13nS
t_f	Fall Time	40nS	28nS	27nS
V_{DD}	Working Voltage	600V	1200V	1700V
D	Duty Cycle	50%	50%	50%
f_{sw}	Switching Frequency	1MHz	1MHz	100KHz
t_{off}	Off Time	160nS	67nS	34nS

MOSFET Power loss equations are taken from reference [22] and the values are calculated based on Vendor's data sheet and application notes

Power loss during conduction or conduction loss is

$$P_{COND} = I_{D(ON)}^2 * R_{DS(ON)} * D \quad (1)$$

Where,

P_{COND}= Conduction loss

$I_{D(ON)}$= On state current

$R_{DS(ON)}$ =On state Resistance

D= Duty Cycle

The switching losses are the sum of two separate losses viz ON time loss and OFF time losses given below. Energy loss during ON time,

$$E_{ON} = I_{D(ON)} V_{DD} \frac{t_{ri}+t_f}{2} \quad (2)$$

Where,

E_{ON}=Energy Loss during ON time

$I_{D(ON)}$= On state current

V_{DD}= Drain Voltage

t_{ri}=Rise time

t_f=Fall time

Therefore, the ON time power loss is given by:

$$P_{ON} = E_{ON} * f_{sw} \tag{3}$$

Where,

E_{ON}=Energy Loss during ON time

$I_{D(ON)}$= On state current

V_{DD}= Drain Voltage

t_{ri}=Rise time

t_f=Fall time

Energy loss during OFF time,

$$P_{ON} = E_{ON} * f_{sw} \tag{3}$$

Where,

P_{ON}=ON time power loss

E_{ON}= ON time energy loss

f_{sw}= Switching Frequency

Therefore, the OFF-time power loss is given by,

$$P_{OFF} = E_{OFF} * f_{sw} \tag{5}$$

Where,

P_{OFF}=OFF time power loss

E_{OFF}= Energy Loss during OFF time

f_{sw}= Switching Frequency

Therefore total power loss,

$$P_{loss} = P_{COND} + P_{ON} + P_{OFF} \quad (6)$$

Using these equations in the values of Table 1 and using the methods for loss calculation from [23], 11.5% device level losses for Si-MOSFET and 5.81% for SiC-MOSFET 1 and 5.67% for SiC MOSFET 2 is obtained. Silicon power electronics is a matured technology, and silicon carbide power electronics is evolving technology. Thus in future even lower losses in SiC transistors can be expected.

4.2. Analytical Loss Calculation of Inverter:

The overall performance of the AC power system is defined by various losses. Different modulation techniques are used in three level inverters to modulate the switches. Based on our review article [2], Neutral Point Clamped 3-Level Inverter (NPC-TLI) is the most efficient topology for renewable applications [2]. However here a notional system based on an analytical model has been created. As explained previously, the loss calculation in real world is dependent on factors solely varying system to system. This specific system which is a clear representation of a DC-SiC based charging system is calculated and calibrated according to the equations mentioned below.

The selection of modulation technique is important to achieve marginal losses in the output current and voltage waveform and decreased harmonic distortion. Several modulation techniques rule the power electronics research arena, however two predominant ones in industry are sine pulse width modulation or SPWM and Space vector pulse width modulation or SVPWM. To solve the positive half cycle of the output voltage in SPWM technique, the voltage drop across Si-MOSFET over a conduction period can be expressed [22] as follows.

$$P_{Cond(MOSFET)} = 1/2\pi \cdot 1/T_s \int_0^{\pi} V_D \; i_D t_{MOSFET} \; (dwt) \qquad (7)$$

Where,

$P_{COND(MOSFET)}$=Conduction Loss

V_D= Voltage drop over condution period

t_{MOSFET} = ON time for the MOSFET,

i_D=Current over conduction period

T_s =switching time of the device given by $1/f_s$ [23].

The MOSFET switching losses during ON and OFF time can be given by,

$$P_{sw} = \frac{f_{sw}}{2\pi} \int_0^{\pi} (V_{DSON} I_{DSON} + V_{DSOFF} I_{DSOFF}) dt \qquad (8)$$

Where,

$P_{COND(MOSFET)}$=Conduction Loss

V_D= Voltage drop over condution period

t_{MOSFET} = ON time for the MOSFET,

i_D=Current over conduction period

T_s =switching time of the device given by $1/f_s$ [23].

The diode loss for this topology is:

$$P_{C(DIODE)} = V_F I_0 + \frac{R_F I_0^2}{1-D} \qquad (9)$$

Where,

$P_{C(DIODE)}$= Diode Conduction Loss

V_F= Diode Forward Voltage

I_0==Ideal diode Current

R_F=Diode Forward Resistance

A three phase NPC inverter contains three legs known as phase a, phase b, phase c. From reference [2], if the topology each leg is studied, it can be observed that contains 4 MOSFETs and two clamping diodes. The same amount of losses are considered in each of the semiconductor devices situated in the same half of the inverter. Similarly in each leg it can be assumed that the MOSFETs to have same amount of losses and the diodes to have same amount of losses.

Thus, the conduction loss of Si NPC-TLI inverter in SPWM modulation is obtained as follow:

$$P_{COND}=3[2P_{C(MOSFET)UP}+2P_{C(MOSFET)DOWN}+P_{C(DIODE)UP}+P_{C(DIODE)DOWN}] \qquad (10)$$

For switching loss the equation can be given by,

$$P_{SW}= 3[2P_{(MOSFET)UP}+2P_{(MOSFET)DOWN}] \qquad (11)$$

Where,

$P_{(MOSFET)UP}$=Power Loss in Upper MOSFETs of leg

$P_{(MOSFET)DOWN}$=Power Loss in Lower MOSFETs of leg

The power loss in the charging capacitor can be given by,

$$P_C = R_{ESRC}\left(\frac{\Delta I_{DC}}{\sqrt{3}}\right)^2 \qquad (12)$$

Where,

P_C= Power loss in capacitor

R_{ESRC} = Equivalent series resistance for the capacitor.

I_{DC}= Capacitor Current

The values from Table 1 and equations 1-6 can be substituted in equation 7-9.

The total loss is given by,

$$P_{TOTAL}=P_{COND} + P_{SW} + 2P_C \quad (13)$$

A 10.64% inverter loss was calculated, putting the values of Table 1 in equations 7-13 and the method mentioned in [23].

4.3. Analytical Loss Calculation of a Rectifier:

To supply DC power to the EV chargers, a three-phase full wave diode bridge rectifier can be employed. Three phase PWM rectifiers are preferred for grid connected applications. But for applications like this, a diode rectifier will be a cheaper and robust option where the source is supplying a fixed amount of load. The average output voltage is given by [22].

$$V_L = \frac{6}{2\pi}\int_{\pi/3}^{\pi/2} V_{mL}\sin(\omega t + 30)\, d\omega t \quad (14)$$

Where,

V_L= Load voltage

V_{mL}= Maximum load voltage

The average load voltage was calculated to be 95.4% of source voltage for SiC 1 and 96.1% for SiC 2, thus giving a 4.6% and 3.9% loss respectively in similar way as inverter [23].

4.4. Analytical Loss Calculation of DC-DC Converter:

For the case of Figure 2, a unidirectional DC-DC converter is used for converting the PV/Wind generated erratic power to amplified smooth DC power. Different approaches of converting that

DC- to charging station can be taken the simplest one being, installing a unidirectional DC to DC converter that feeds power directly to the charging station as shown in Figure 2. Unidirectional converters are simple in design thus reducing system cost and power losses. Unlike dual active bridge converter as shown in Figure 1 for the AC counterpart, it does not need a transformer, making it lighter in design as well. For a national and international scenario such as this one it is scalable and perfect. The piecemeal loss calculation [22] is given below:

The Power loss in the inductor [23] is given by,

$$P_L = \frac{1}{T_S}\int_0^{T_S} R_{ESRL}(i_L^2(\text{t}))\ \text{dt} \quad (15)$$

Where,

R_{ESRL}=Equivalent series resistance for the inductor.

I_L= Load current

T_s =switching time of the device given by $1/f_s$

The Power loss in the capacitor is given by

$$P_C = R_{ESRC}(\frac{\Delta I_L}{2\sqrt{3}})^2 \quad (16)$$

Where,

R_{ESRC}=Equivalent series resistance for the inductor.

The loss occurred in diode

$$P_D = I_o V_D(1-D) \quad (17)$$

Conduction loss in MOSFET is given by equation (1) and switching loss is given by,

$$P_{SW} = I_{DON}^2 \cdot R_{DSON} \cdot D + I_o V_D(1-D) + R_{ESRL} I_0^2 + R_{ESRC}\frac{\Delta I_0^2}{12} \quad (18)$$

(Variables are of the same interpretation as previous equations.)

Duty cycle is directly proportional to power dissipation and 50% was decided to be optimum for this application. Reference [24] sheds more insight on this issue. For Silicon device the loss at 50%

duty cycle was found to be 160W in terms of total losses. For SiC it was 10W per device. It is consistent with the loss data reported in section 7. Taking into consideration the duty cycle of 50%, input of 1200V for SiC 1 and 1700V for SiC 2 and load resistance of 17 mΩ and 410 mΩ respectively, the losses calculate to be 8.3% and 7.81% respectively. Here a fixed duty cycle has been chosen for comparison, as shown in Table 1. Power loss with varying duty cycle for SiC and Si power electronics is shown in Figure 4.

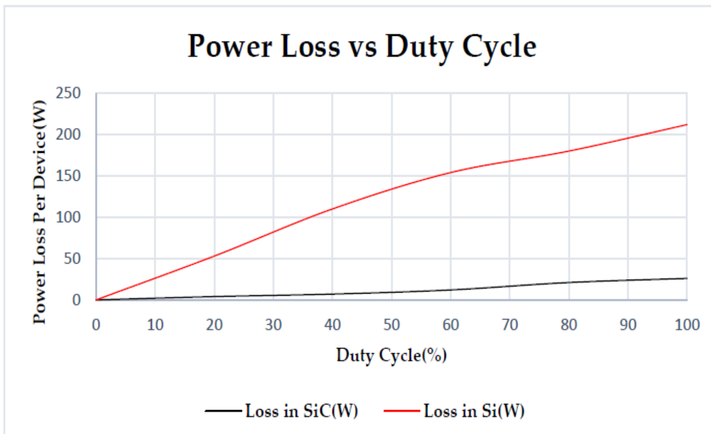

Figure 18 Power loss per device vs duty cycle for Si and SiC devices.

5. Model Validation:

Charging time data calculated by the model developed in this paper are compared with the experimental data reported in the literature for Si [24] and for SiC [25] based XFCs. As shown in Table 2, excellent agreement is observed between our calculated values and the experimental values.

Table 6 Charging Time Reduction Comparison with Literature

Vehicle	Pack Voltage (V) & Approximate Energy kWh	Range (mi)	Max Charging Power kW	Si XFC from Ref[24] (mins)	Our Si XFC model(mins)	SiC XFC from ref [25] (mins)	Our SiC XFC Model

Tesla Model 3 long range	400 & 78.3	350	250	28	23		20
Porche Taycan Turbo S	800 & 93.4	200	270	22.5	18		18.7
Xpeng EV	800 & 250	125	480	-		5	4.5
ABB terra HP	400 & 150	200	350	20 min	17.5		15

6. Charging Time Calculations of SiC Power Electronics Based XFC:

Today XFC is recommended only a limited number of times to protect battery health. On the other hand fast charging is required for long-distance travel automobiles and is the only solution to electrify transportation of long-distance heavy-duty vehicles. In this section the charging time reduction, improved battery health and power system loss reduction with the implementation of SiC power electronics will be discussed. Higher efficiency of the power electronics provides lesser stress on battery and powertrain [25].

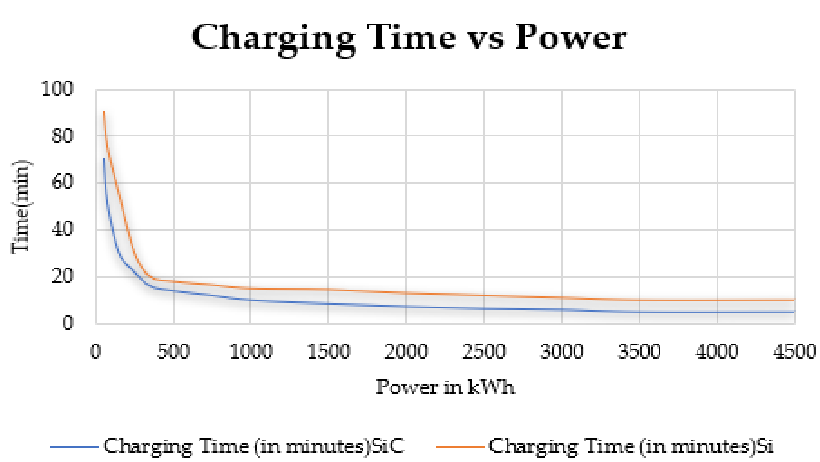

Figure 19 Reduction of charging time with increasing charging power (kWh) for Si and SiC Power Electronics based XFC.

To reduce charging time, battery pack voltage is increased to obtain maximum charging power and comes with additional complexity of a larger BMS. To accommodate the higher voltage, the number of cells connected in series must be increased. As an example, twice the number of cells must be connected in series for an 800V SiC based XFC as compared to the 400V Si based XFC. Additional circuitry like current sensors, controllers and temperature sensors etc. remain practically unchanged. The charging time also depends on the ambient temperature and circuit's heat dissipation capacity [26]. Figure 5 shows the results of charging time as a function of power with Si and SiC based power electronics as the variable. An ambient temperature of 25°C was assumed. As observed from Figure 5, a steep decline in time is noticed up to 1MW, thereafter the heat loss increases and charging time get affected by the losses, and hence the time reduces less drastically than observed at the lower wattage.

Figure 6 shows the capacity of charging at different ambient temperature for Si and SiC based XFCs. A standard high power battery pack of 1.2 MW was considered. As observed, the capacity of charging is very low at lower temperatures and is maximum at 25°C. At all temperatures, the capacity of charging is higher for SiC XFC.

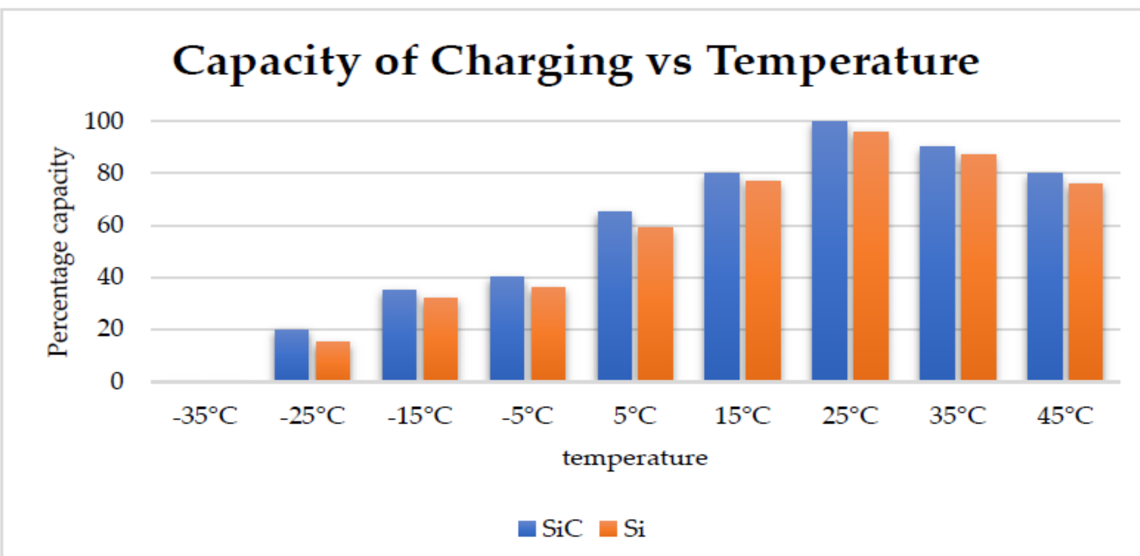

Figure 20 Capacity of charging as a function of temperature for Si and SiC based XFCs.

Connecting a greater number of cells to operate at a higher power level comes with the drawback of deteriorated state of health (SOH) of batteries. The improvement of battery health while using

SiC based fast charging is achieved by lesser heat exposure and better temperature control. The losses in Li-ion battery can be classified into two major types viz cycle life loss and calendar life loss. Overcharging the battery contributes the loss of cycle life. As an example if a 1.2 MWh battery is supposed to have 2000 cycles as per datasheet and if the charge is controlled to 1.1 MWh, then it is possible for the battery to last 2500+ cycles [27]. Calendar life loss is defined by the loss of health in battery after storing energy for typically 6-10 months [27]. A semi empirical formula for total loss [28] is given below.

$$Q^{total\ loss}(\delta t) = B_1 e^{B2Irate} I_{rate}\delta t + 0.5 f e^{-Ea/RTb} t^{-1/2} \delta t \qquad (19)$$

Here B1 and B2 are the polynomials of the temperatures of the battery Tb. Irate is the rate of current for charging the battery and R is temperature coefficient. Therefore the model is highly temperature dependent. When the total loss is calculated over a period using different scenarios of DC power based XFC, the increase in battery health is observed. An energy dense battery of 1.2MWh is used in calculations in this paper. Table 3 shows the state of health (SoH) data for both Si and SiC based XFC.

Table 7 SOH with Age in Time Varying DC XFC Usage for Si and SiC Power Electronics Enabled Battery Energy Storage System

State of Health (SoH) (%) with Time Varying DCFC Use						Battery Age
Never		0-3/Month		>3/Month		(Months)
Si	SiC	Si	SiC	Si	SiC	
1	1	0.95	1	0.92	0.956	3
0.95	0.97	0.89	0.94	0.85	0.91	6
0.92	0.95	0.85	0.915	0.82	0.89	12

0.88	0.91	0.82	0.89	0.79	0.865	24
0.85	0.88	0.79	0.87	0.765	0.85	36
0.83	0.86	0.76	0.855	0.73	0.845	48

Ambient temperature has a direct impact on the performance and reliability of lithium-ion batteries (LIBs). Battery capacity and cycle life are affected by operating temperature. Ideal operating temperature for Li-ion batteries is 15-35°C [26]. In general the useful life of LIBs can range between 3,000 to 5,000 cycles [29]. However, with optimal charging, the useful life can be up to 7,000 cycles [29]. Operating at higher temperatures will reduce cycle life due to cell degradation [30]. Continuous operation at higher than 35°C (95°F) will typically reduce battery cycle life by 50% [31].

Figure 7 shows the energy efficiency as a function of power level both for Si and SiC based XFC. It is clearly evident from Figure 7 that at a higher power level, the fluctuations in energy efficiency are far lower in case of SiC than the corresponding values for Si. The efficiency almost decreases 20% at higher power levels for Si but remains in the range of 5% for SiC counterpart. This will not only reduce the loss in generated power but in addition will help battery health, powertrain health and the associated control equipment to operate at a stable operating condition.

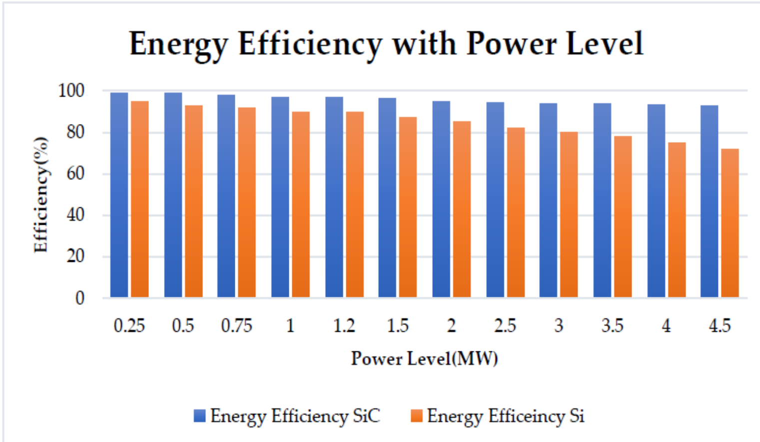

Figure 21 Energy efficiency in Megawatt level charging

7. Heat Sink Size Reduction:

As shown in Figure 1, currently AC electricity infrastructure is used to provide charging of EVs which is based on silicon power electronics. To calculate the size of heat sink, first the system losses are calculated. The analytical model described in section 4 is used to calculate the losses of two SiC modules. The subsequent losses and the comparison with silicon counterparts [32] is given in Table 4.

Table 8 Charging Time Reduction Comparison Using SiC Counterparts

Conversion Level	% Loss reported in Silicon Devices [28]	%Loss derived for SiC1	%Loss derived by SiC2
Inverter	15	10.64	10.64
Rectifier	6.1	4.6	3.91
Chopper	9.2	8.3	7.81

After calculating the percentage losses of inverter, the heat sink has to be designed based on the available system parameters. But the more universal approach is to calculate the heat sink per module as explained below.

There is one heat sink solely responsible for inverter bank and another one responsible for the rectifier bank. For SiC XFC based on DC power as input, only one heat sink is necessary for DC-DC converter bank. For this paper three devices were used. Upcoming SiC technology of reference

[21] was considered although the switching frequency was lower, but the potential for improvement was bserved as a charging time reduction was calculated. To show the advantages of SiC system, a quantitative power loss analysis is performed based on the parameters of Table. 1. In the calculations, the switching loss of diode is neglected, because it is much smaller compared to the switching loss of IGBT or MOSFET. The sinusoidal pulse width modulation (SPWM) is employed in the control of inverter. Although different devices are used in the two systems, the calculation methods are identical. This method is applicable for any system size. The AC-DC and the DC-AC conversion stage can be designed in two ways. A solo inverter with high power rating equipment or an inverter bank with multiple inverters is connected. The later approach has been used for high power applications for reasons such as scalability of the system, ease of construction and carrying load, safety concerns and load sharing, and in case of fault in one inverter the rest of the bank can carry on the load.

Table 9 Heat Losses at Different Stages of Inverter Si -MOSFET

Conduction loss (per device)	MOSFET 70 W
Conduction loss (per device)	Diode 10 W
Switching loss (per device)	80 W
Total loss (6 MOSFETs+6Diodes)	960 W
Efficiency	89.36%
Total Losses	960W
Output Power	9.02kW

Table 10 Heat Losses at Different Stages of Rectifier Si -MOSFET

Diode Conduction Loss	10W
Total Loss	60W
Efficiency of Bridge Rectifier	95.4%
Output Power	8.96kW

Therefore in this section the heatsink design for each of the segments of inverter and rectifier banks will be calculated and compared to similar DC-SiC bank. A scaled down version is used here for practical dimension purposes as available in industrial datasheets. The system mentioned in this paper is massive, and no vendor has yet provided a datasheet for such design of a heat sink. Undoubtedly, if the system is stressed and made larger for XFC charging of high-power vehicles, the banks can be added together to operate smoothly. So a heatsink capable of removing 1,020W of heat must be selected. Reference [32] uses an identical system for 1800W heat loss. Selected heatsink was based on similar criteria.

Table 11 Heat Sink Details

Topics	Inverter heat sink
Power Loss (Per Device)	160W
Efficiency	89.36%
Package size (Calculated from datasheet)	170mm^2
Heat Sink Size	Width (WD)= 300 mm, Depth (D)= 100 mm, Height (H)= 40 mm

Heat Sink Weight	3.6Kg
Thermal Resistance $R_{heatsink}$	0.021°C/W

	Rectifier heat sink with SiC 1	Rectifier heat sink with SiC 2
Power Loss (Per Device)	10W	12.1W
Efficiency	95.4%	94.5%
Heat Sink Size	WD=50mm,D=20mm,H=15 mm	WD=55mm,D=22mm,H=15 mm
Heat Sink Weight	0.6Kg	0.73Kg
Thermal Resistance $R_{heatsink}$	0.021°C/W	0.0196°C/W

For DC-DC converter one SiC MOSFET and one diode is used in the system constituting 8.3% of losses. So for a similar sized bank the losses will be half of the total rectifier and inverter bank. Hence the heatsink size will be half as well. But SiC has better power handling capability and the number of devices used in the circuit is lesser. The voltage level shown in Figure1 and 2 are 1500VDC- 220KV for inverter and 1500V to 380V for unidirectional rectifier / DC-DC converter. In both cases the number of devices is same. Using these numbers, SiC-MOSFET DC-DC converter heatsink is 28.6 % that of the inverter plus rectifier bank. But there are additional negligible losses. So a 30% round up number was estimated. An exact precise number in this scenario did not seem reasonable as every system will have different components. Using the new upcoming technology of SiC 2, slight increase in heat was observed due to higher RDS (ON), yet it was 44% of the size of the inverter plus rectifier bank in a Si counterpart.

After reducing the dissipated heat at component level, heat pump can be used to further reduce the size of the heat sink. In case of Tesla model Y [33], a heat pump is used to collect the dissipated heat from battery energy storage (BESS) and converter bank to heat or cool the car. For heating below -10 0C this method is highly effective [34]. The system efficiency is improved by a liquid cooled condenser where the BESS and converters reject heat and it's moved around in passenger cabin, battery, and the drive unit and sometimes outside ambient temperature to improve system efficiency [35]. The sizing of heat pump was a critical aspect [36] to determine the overall cooling system size reduction. Almost 7-30% heat is recycled using this technology depending on the outside ambient temperature [33].

A similar technology for XFC heat reduction is proposed in this paper. The residue heat from the converters may be compressed and used to heat or cool the adjacent control rooms or used for other purposes. Calculating the correct size of heat pump is imperative to ensure the heating technology is not dissipating too much heat while propagating through the pump. Several factors like the kilojoules needed for the space, the direct sunlight exposure of the recipients, the energy rating of the heat pump etc. are important factors to be considered while calculating the heat pump size [36]. By accurately calibrating the dimensions, Tesla was able to make their heat pump 300% more efficient than their resistive heating system [37]. Since the system size for a charging station is larger than that of a vehicle, the dissipated heat during propagation should be higher. The recalibrated heat sink values for different level of converters using both SiC and heat pump are given in Table 12.

Table 12 Heat Sink Dimensions Calibrated for Each Converter Bank after Installing Heat

Converter Bank	Heat Sink Size
Rectifier Bank	WD=20 mm, D= 10 mm, H= 5 mm

Inverter Bank	WD= 70mm, D= 50mm, H=10mm
DC-DC Converter Bank	WD= 30mm, D= 20mm, H=10mm

Assuming constant current, the thermal loss over operating time was calculated with the given RDS(ON) and the standard circuit heating formula H= I2Rt. These results are shown in Figure 8 both for Si and SiC based XFC.

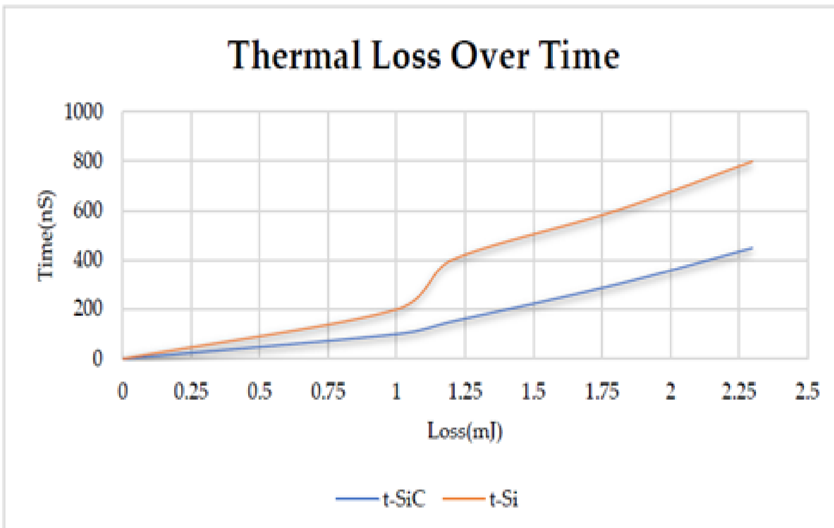

Figure 22 Thermal loss with time representing the volume reduction of heat sink by replacing Si with SiC

8. Manufacturing Cost Reduction of Silicon Carbide Power Electronics:

The cost of SiC based power electronics can be significantly reduced in very near future, it is pretty evident [38]. Attributable to the high growth of EVs, Silicon carbide modules are providing higher power density of motor drive of electric vehicles [39]. No supply-chain issues in the manufacturing of its related power electronics are predicted due to the abundance of elements of SiC. Higher performance, higher reliability, higher yield, and lower cost of ownership of SiC based power electronics will be provided if policies in favor of electrification of transportation, volume manufacturing, single wafer processing [40] and large diameter wafer manufacturing are implemented [41]. Silicon carbide fabs are migrating from 150 mm wafers to 200 mm wafers [42]. With progress in technology, the feature size of transistors and defect density will also be reduced. Akin to Si, the cost of SiC power electronics with the use of 300 mm SiC wafers will further reduce. Reminiscent of the growth of Si based nanoelectronics and power electronics, the growth of SiC based power electronics is expected to evolve in a similar fashion. Recently, the author of Reference [43] has analyzed the current and projected cost of silicon carbide die.

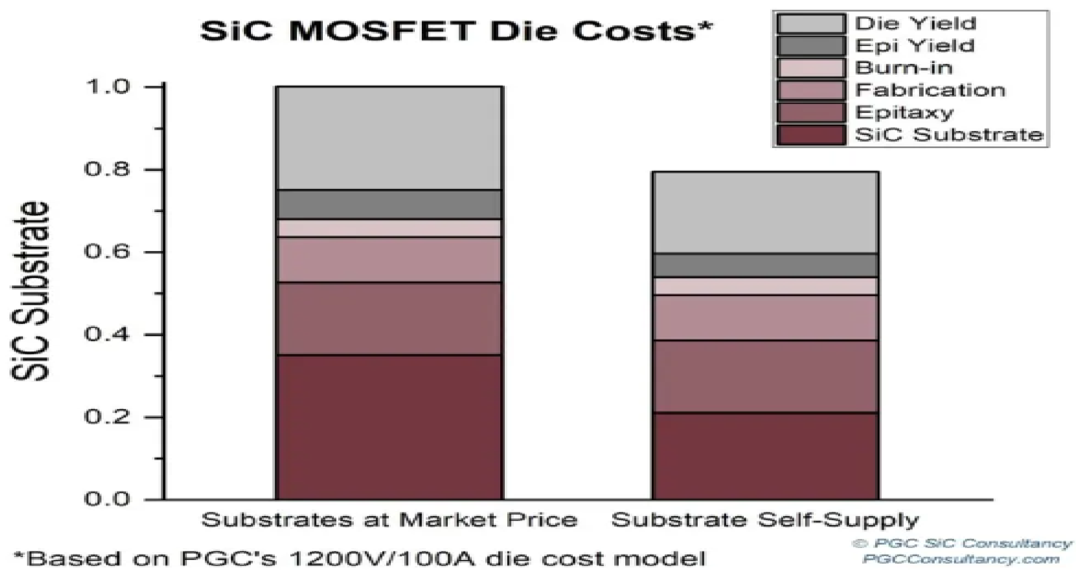

Figure 23 Cost breakdown of a SiC MOSFET die. Data on the left side shows that SiC die manufacturer purchased SiC wafer from the market. On the other the hand, data on the right side shows in-house manufacturing of SiC wafer as well as die [43].

As shown in Figure 9 [43], companies having in-house manufacturing of SiC wafers have the advantage of lower cost of SiC die. Based on industrial trends, the author of reference [43] has also projected the substrate cost, defect density, die size and die cost reduction from current values to year 2030. Due to current geo-political event, we expect that the electrification of transportation will accelerate and the graphs shown in Figure 10, may even reduce faster than projected in reference [43].

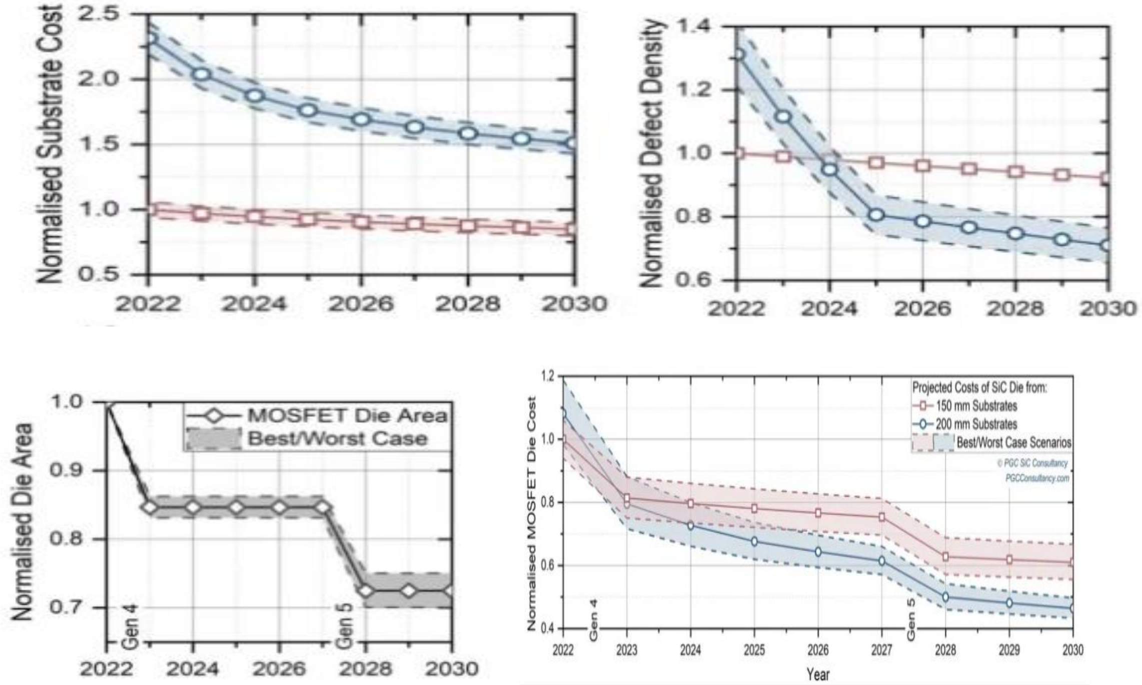

Figure 24 Current and projected trends to year 2030 in the reduction of (a) cost of SiC wafer, (b) defect density, (c) die size and (d) die cost [43].

The use of silicon carbide-based power electronics will also be enabler of medium voltage DC to high voltage DC converters and high voltage DC to medium voltage DC converters that can provide 100 % DC power for EV charging infrastructure [44]. Other markets such as power networks, high frequency, and ultra-high-power electronics for harsh environments etc. will also progress with the success of SiC power electronics. The lower cost of SiC based XFCs will contribute to the growth in other markets as well.

9. Conclusion:

In this paper the design and analysis of XFC based on silicon carbide power electronics has been provided. As compared to Silicon power electronics based XFC, reduction of charging time, higher power conversion efficiency, reduced size of heat sink, and improved battery state of health are obtained in case of SiC power electronics XFCs. For heavy duty trucks SiC based XFC may be the only practical solution. The use of larger diameter silicon carbide wafers will further reduce the cost of SiC based power electronics. Using free fuel energy sources namely solar and wind and the use of lithium-ion batteries for electrical power storage, it is possible to implement end-to-end DC system for power generation, power storage, power transmission and power distribution. Combining such DC power network and SiC based DC power XFC will provide revolutionary solution for electrification of transportation.

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CHAPTER FOUR

AN 800V END TO END SIC POWERTRAIN TO ACCOMMODATE EXTREMELY FAST CHARGING

1. Introduction

The sea level is rising because of the emission of harmful greenhouse gases. Studies suggest that earth is in the middle of the fifth mass extinction solely enabled by the greenhouse gas (GHG) produced by humanity [1]. An unusual heat wave is already almost upon all the countries [1]. The ozone layer is depleted because of the warming of the environment resulting from pollution. The mobility industry plays a vital role in the global economy. It enables trillions of dollars in trade every year. It is also the most significant source of avoidable GHG emission, contributing almost 19% of the total GHG emissions [2]. This disaster is avoidable by adopting renewable energy and integrating it with energy storage devices such as batteries and changing the transportation industry to electric only [2]. The economic consequences will be significant to transform a heavily fossil fuel driven economy. Oil has long been used as a geopolitical weapon [3]. Electrification of almost everything is the only solution to handle climate emergency [4]. As shown in Figure 1, by 2050 Internal combustion engine is expected to be replaced by EVs [5]

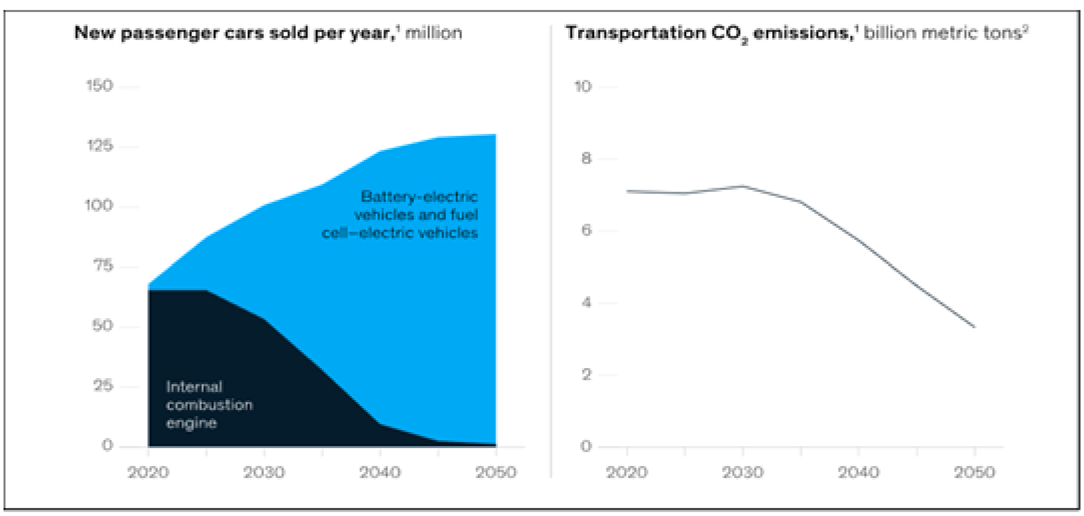


Figure 25 Car sales every year in ICEV and EV category [5]

The adaptation of electric vehicles around the world is very clear as the EV sales more than doubled in 2021 [6]. Bloomberg news reports that the world's EV fleet will soon surpass 20 million [7]. The revolution is led by China and Europe with USA a distant third [7]. In a recent review paper, we thoroughly reviewed the roadblocks and cited the possible avenues to implement a green charging infrastructure for electric vehicles [8]. In United States, the adoption of EVs is discouraged by the efficiency of fossil-fueled vehicle's fast refueling experience and the reservation towards 100% green power generation, unlike Europe and China [5]. To overcome these barriers a silicon carbide power electronics based green charging infrastructure is proposed [8]. In order to increase the overall system energy efficiency, replacement of Si operated powertrain must be implemented for keeping up to the higher-power charging infrastructure. It must be noted, only increasing the charging power levels is futile if the EV itself has a low power drivetrain n incapable of accepting the high-power charging. Clearly, these issues go hand in hand. According to recent data, a typical high-end battery electric vehicle (BEV) like Tesla Model S has a range of 405 miles. With Tesla Supercharger of 135kW, this means a charging time of 27 to 40 minutes is estimated for the 400V silicon power electronics based power drivetrain. Whereas, refueling an IC Engine Vehicle (ICEV) will only take 5-10mins. This discourages customers to adapt to EVs due to range anxiety. In recent paper, authors discussed 500kW-1.2GW level of charging being possible with SiC power electronics-based charging infrastructure, however the EV simply cannot accept the high level of charging with a 400V drivetrain. The cable limitations must be incorporated while calculating the charging time as faster charging will increase the current rating by three to six times, conduction loss is the square of current rating meaning anywhere between nine to thirty-six times making the cable bulky and necessitating a costly cooling system to avoid an overheating explosion [9]. Therefore, the voltage rating of the powertrain must be increased to avoid increase in current rating of the powertrain to avoid aforementioned limitations. Apart from reducing current limit a high voltage powertrain will provide benefits including but not limited to battery current limit remaining same but charging getting faster, lower I2R losses, smaller current rating in motor reducing their size. A set of publications that discuss 800V powertrain has been reviewed in the literature [10]-[13]. However a complete evaluation of fully SiC powertrain against a fully Si Powertrain of similar voltage level is necessary, and this paper fills the gap in recent research.

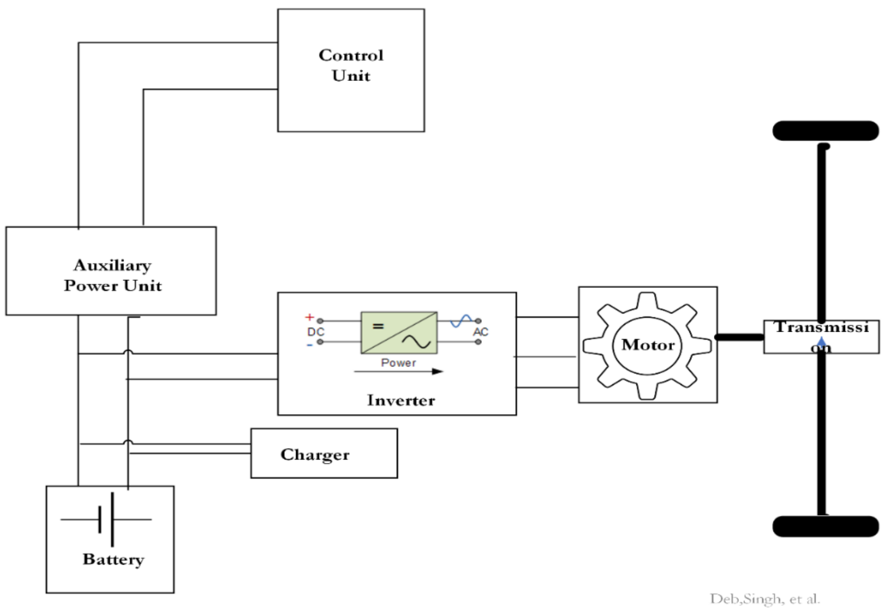


Figure 26 Typical Structure of a BEV Powertrain

Figure 2 shows the architecture of a BEV powertrain where the high-power battery is the main source of power that provides for the electric motor and a control unit that supplies power to the internal sub-systems. The motor is the high-voltage (HV) load, and the accessories are the low voltage loads. An in-depth analysis of this will be done in the next sections of this paper. However, the battery voltage level for most of the passenger cars today are 250-450V. If we employ an 800V system, the system must be adaptable to the new voltage levels, hence power electronics plays the most crucial role.

A comparative study of the physical properties of the devices (Si and SiC) in Table 1, gives an idea of its higher efficiency, lower loss and overall reduced weight thus making the Powertrain more efficient.

Table 13 Comparison of Physical Properties of Si & SiC for APU

Properties	Si	SiC
Energy Gap(eV)	1.17	3.12
Electron Mobility(µn)	1700	980
Thermal Conductivity (W/cm.°C)	1.5	4.9
Saturation Drift Velocity vs. (cm/s)	1	2.2
Relative Dielectric Constant : ϵs	12.4	10.1
Breakdown Field: EB (V/cm)	0.3	3

The paper is organized as follows. The next section selects appropriate power electronics device for evaluation. Section 3 explains the modelling approach. Section 4 evaluates the impact of higher voltage battery energy storage system (BESS). In section 5 we have explained the importance of power electronics in Powertrain. Section 6 covers the motor output improvement by using SiC based power electronics. Section 7 and 8 give a brief overview of mechanical stress and charger in EV. Section 9 evaluates the auxiliary power unit in powertrain. Conclusion of the paper is given in section 10.

2. Parameter selection:

The parameter selection is pivotal element in this research and authors researched a multitude of automotive MOSFETs currently available in the market to select the top two candidates for analysis. The SiC MOSFET is UnitedSiC UF3C170400K3S [14] and the Si MOSFET [15] is Infeneon IPD80R2k7C3A. The devices were selected because in both categories the highest power device applicable for transportation electronics must be selected to compare at their optimum operating points. The core model will be replaced with these two devices enabled boards and results will be analyzed. The key parameters are listed below in Table 2.

Table 14 : Parameter Selection

Symbol	Attribute	Si Infeneon IPD80R2k7C3A [14]	SiC UnitedSiC UF3C170400K3S[15]
I_{DON}	On Time Current	6A	14A
R_{DSON}	On Time Resistance	2.7Ω	410mΩ
t_r	Rise Time	15nS	13nS
t_f	Fall Time	18nS	27nS
V_{DD}	Working Voltage	800V	1700V
D	Duty Cycle	50%	50%
f_{sw}	Switching Frequency	100KHz	100KHz
toff	Off Time	72nS	34nS

3. Modelling:

The modelling approach is based on reference [16] which represents every subsystem in equation blocks. The equation blocks are connected through signal blocks that are updated at every time step. In every subsequent section the working equations will be presented and analyzed. The overview of the notional model is given in the simplified block diagram in Fig 3.

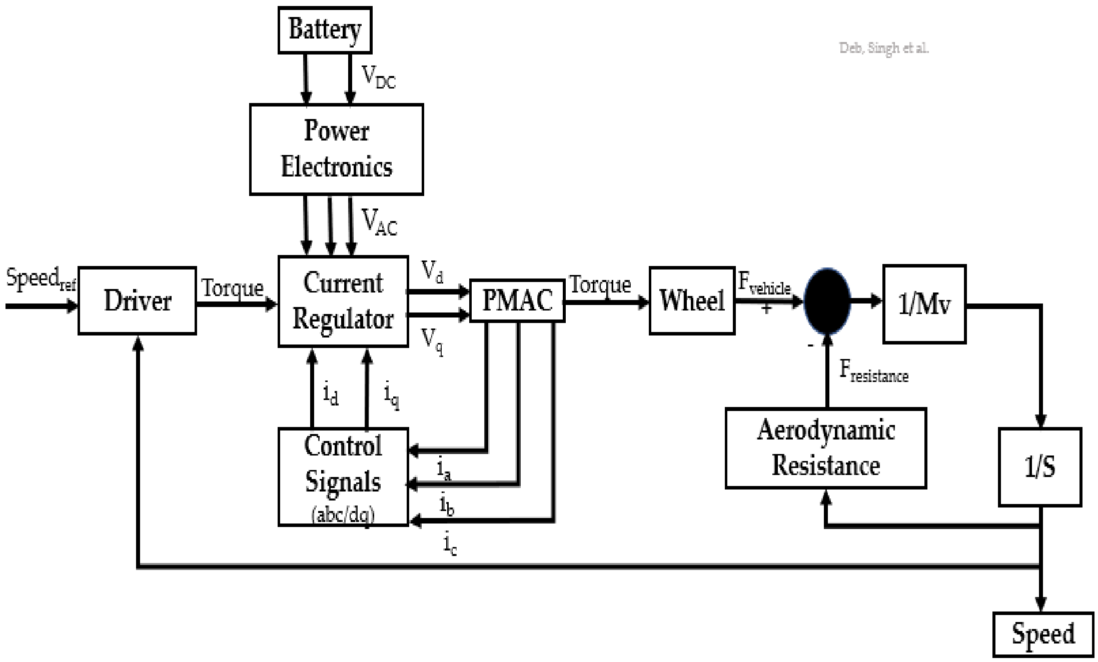


Figure 27 Simplified block diagram of the equation model.

4. Battery Energy Storage system (BESS):

With the emergence of EV revolution, researchers keep developing energy dense batteries. However, developing a high-performance battery without adequate conversion system is futile. In order to find the suitable battery system for an 800V powertrain the key parameters of evaluation are energy density, power density, cycle life, calendar life and price/kWh [17]. The safety and volume are also crucial requirements for the battery manufacturers.

Energy efficiency and self-discharge also needs to be considered in a detailed level before approving a model [17]. Although the battery size is determined by the energy to be delivered to the powertrain, it must be mentioned that the equation representing relationship between car range and battery density is a complex one instead of a linear equation. The higher the battery weighs (range 150kg-500kg) the lesser gets the system efficiency. This in turn impacts the power electronics design of the system too. Automotive MOSFET and IGBT manufacturers have been constant suppliers of Si based 650V devices for the circuit board development of powertrain. Typically 96 Li-ion cells are connected in series, each having a voltage rating of 4.2 volts [10]. Therefore the peak output remains 403.2V. Which is compatible with the 650V peak power transistors being used in typical drivetrains. This has worked well so far for the typical 50kW DC fast chargers. But with increasing charging levels the current rating of the cables keeps increasing hence encouraging us to use the 800V battery packs.

The latest cooling techniques make the cable rating around 500A without compromising the weight. The cable also needs to be flexible enough to be handled by the EV owner. Hence the cooling of charging cables go hand in hand with the battery sizing of powertrain.

In this paper we have considered two 800V buses. The 800V Si is notional whereas the 800V SiC is akin to the Porche Taycan. The industry model of 400V Si Powertrain was used as a reference to create the 800V Si bus. Porche Taycan can charge in 18 minutes for the SoC of 5%-80% but the range is 212 km whereas the 400V industry models such as Tesla model 3 has a range of 360 km [11]. It must be noted that the two companies mentioned above utilize different design perspectives in their powertrain model apart from the design of Power Electronics [12].

The industry models of 400V Si bus also uses a high current of 661A which remains unsafe. In recent times several instances of vehicle catching fire due to high current in batteries have been reported [18]. This could be logical at this point due to the short design of the cable minimizing physical stress on the consumer while charging. On the other hand, Porche Taycan achieves a peak charging power of 270 kW with a maximum charging current of 340 A [13]. Nonetheless, for fair comparison, we have limited the current to 600A for both the models. Parameters used in this paper are given in Table 3.

Table 15 Battery Parameters for 800V BEV [18]

Type	No of series connected cells	BMS Cost	Cable and equipment rating
800V Si	180	2*(592$)	800V
800V SiC	192	1.3*(818$)	900V

The charger power input Pin and charger power output Pout are given below:

$$P_{in} = \sum_{i=1}^{N} \int_{t_s}^{t_s+t_c} I_{DC}(t)\, dt \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$P_{out} = \sum_{i=1}^{N} \int_{t_s+t_c}^{t_s+t_c+t_d} I_{DC}(t)\, dt \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Here t_s, t_c and t_d are charge start time, charging time and discharging time respectively. The difference between input and output power is the loss encountered due to higher charging current. For passenger EV, the results are shown in Figure 4.

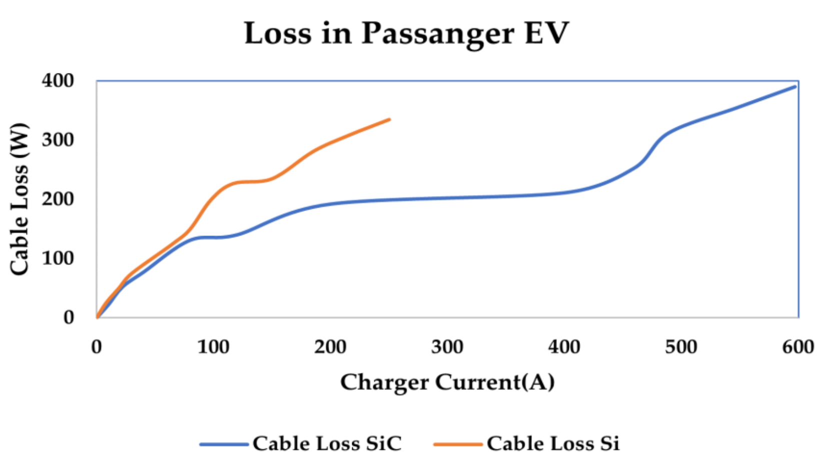


Figure 28 Cable loss for passenger vehicle using 800V BESS

A similar approach with higher power components was used to get the output for heavy duty vehicles. These results are shown in Figure 5.

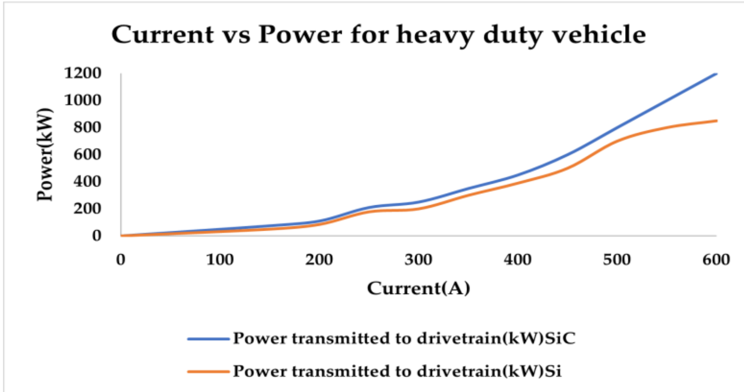


Figure 29 Cable loss for heavy duty vehicle using 800V BESS

The replacement of SiC also increases the State of Health (SoH) of the battery due to the lesser exposure to heat. The battery loses its health due to two types of aging, calendar aging and cycle aging [7]. To calculate these losses a semi empirical formula for total loss [8] is given below.

$$Q^{\,total\ loss}\,(\delta t) \;=\; B_1 e^{\,B2Irate}\, I_{rate}\delta t \;+\; 0.5 f e^{-Ea/RTb}\, t^{-1/2}\,\delta t \;\ldots\ldots\ldots\ldots\ldots\ (3)$$

Where,

B_1 & B_2 = polynomials of the temperatures of the battery

T_b= temperatures of the battery.

I_{rate} = rate of current for charging the battery and

R= temperature coefficient.

It is obvious from equation (3) that total loss of power is largely dependent upon temperature. The temperature is directly related to voltage level of the BESS. Therefore the enhancement of BESS will age the battery faster if the heat dissipation is not controlled. The loss is calculated over a different time period to observe the SoH using the Si and SiC power electronics for powertrain. The results are shown in Table 4.

Table 16 Comparison of State of Health for a 800V BESS using SiC and Si

Development in State of Health (SoH) (%) with charging with a 800V BESS				
0-3/Month		>3/Month		Battery Age (Months)
Si	SiC	Si	SiC	
0.92	0.95	0.88	0.90	3
0.88	0.90	0.84	0.88	6
0.845	0.88	0.78	0.85	12
0.81	0.85	0.75	0.82	24
0.77	0.83	0.72	0.79	36
0.72	0.81	0.69	0.75	48

Table 3 shows improved results with SiC based power electronics. So we see a significant increase in SiC based algorithms. However, it is a tradeoff with the additional monitoring and computational complexity for the higher-powered battery management system (BMS). The pack voltage also impacts SoH as mentioned before and in turn reliability. Despite all these facts it is a fair tradeoff in terms of reliability and customer convenience.

5. Power Electronics:

The reduction of power loss in switching devices comes with a twofold benefit. First reduction of the losses in enhanced power conversion efficiency and the reduction of cooling components. For small systems the power loss reduction in switching devices might not be significant but for higher power vehicles such as heavy-duty trucks the power loss reduction is very important in terms of both power conversion efficiency and cooling reduction practices. Hence the implementation of

SiC is very important for higher power electric vehicles. This might also unfold the possibility of air cooling instead of liquid cooling in passenger vehicles [19] [20] In this section we will evaluate the power loss in 800V powertrain for two most important power electronics components as follows.

5.1.Inverter:

In BEV (or PHEV or HEV) the output of the battery is converted into AC by an inverter and fed to the induction motor or permanent magnet synchronous motor. In case of brushless DC electric motor (BLDC) or permanent magnet DC motor (PMDC) a DC-DC converter is used to smoothen the output of the battery [7]. Here the focus remains in order to compare the electrical performance of the Si and SiC powered 800V powertrain, we have used the most used topology, i.e. the 2 level, 3 phase voltage source inverter (VSI) [21]. The center of focus remains the power loss in switching devices during the conversion as known as conduction losses and switching losses. Apart from the current and voltage rating, the power loss also depends on the switching techniques of the converter. Sinusoidal pulse width modulation (SPWM) and space vector pulse width modulation (SVPWM) are the most commonly used switching techniques due to their robust approach [2].

The conduction loss in MOSFET is given by [20],

$$P_{cond} = R_{on}.I^2.(\frac{1}{8} + \frac{M\cos\phi}{3\pi}) \text{ ……………………….(4)}$$

The conduction loss [18] in Diode is given by,

$$P_{cond} = \frac{1}{2}(V_D.\frac{1}{\pi} + R_{on}\frac{I^2}{4}) - M\cos\phi(V_D.\frac{1}{8} + R_{on}\frac{2\pi}{3}) \text{ ………..(5)}$$

Where, in equation (4), Pcond is the power during the ON state of the MOSFET, Ron is the on-state resistance, I the on-state current, M is the modulation index and cosφ is the power factor. For diode equation of (5), the notations remain the same added with VD as the diode voltage drop.

The power loss has been calculated in 100 kHz and 400kW output devices. The charging time as a function of charging power for both Si and SiC power electronic reduction in charging time for both charger has been shown in Figure 6. For all values of charging power, lower charging time is obtained for SiC power electronics. This scalable design can be extended till 1.2GW for the heavy-duty chargers.

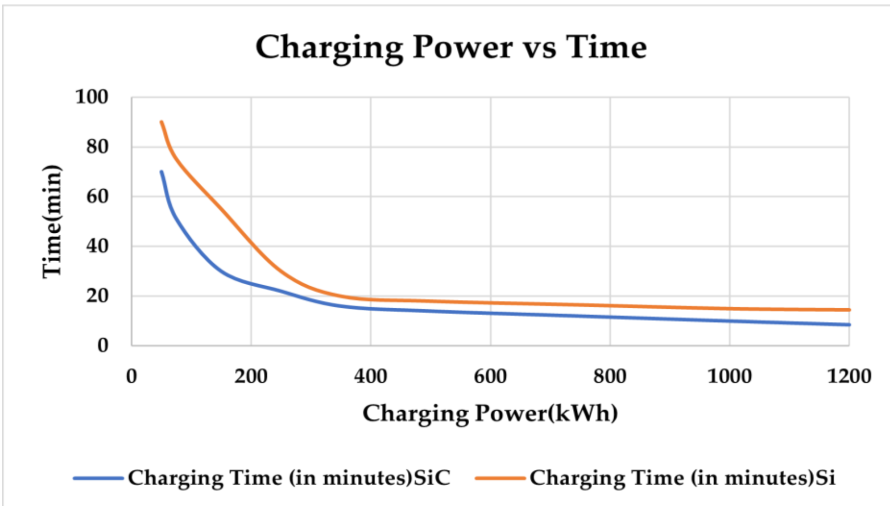


Figure 30 Reduction in charging time due to increase in inverter output

For the other less used topologies the advantages and disadvantages are listed in Table 3 in reference [20].

5.2.DC-DC Converter:

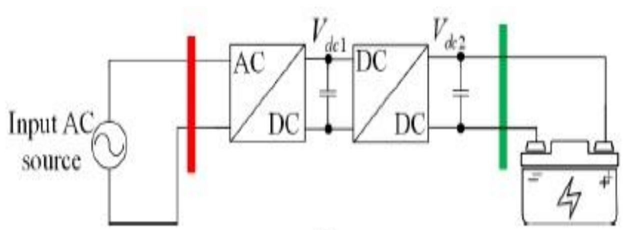


Figure 31 Non isolated DC/DC converter

The DC-DC converter is crucial as its function remains to smoothen the flow between Li-ion battery and motor and in case of DC motors it replaces the inverters. It roughly comprises of 30-40% of the total converter weight depending upon the machine used at the end [20]. The individual chip area however is larger than inverter, therefore, despite being smaller in size the losses are accountable in total. This also brings attention to the fact that due to the denser packaging technology of SiC converters, it's evident that they are a better fit in terms of weight and size for DC-DC converters in traction powertrains. The loss calculation for DC-DC converter is done using a similar approach as previous sections. The power loss is calculated during ON time of the IGBT and the equations below are fed into the simulator.

$$P_{COND} = (V_D I_L + R_{on} I_L{}^2)(1-D) \text{ ……………. (6)}$$

$$P_{sw} = f_{sw} E_{TT} \frac{V.I}{V_{nom}.I_{nom}} \text{ ……………………. (7)}$$

Where the P_{cond} is the power during conduction cycle, P_{sw} is the power during switching of the device, f_{sw} the switching frequency, E_{TT} the reverse recovery emf, V_{nom} and Inom the nominal current and voltage respectively.

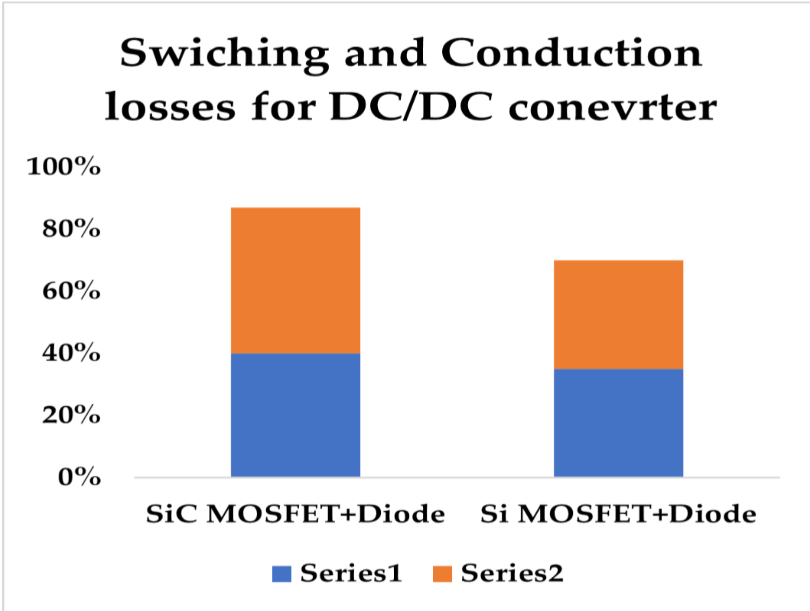


Figure 32 DC/DC converter component loss comparison.

Using equations (6) and (7) the loss can be shown in this graph. The blue region denotes the MOSFET conduction and the orange region denotes the diode conduction for the MOSFET+DIODE duo used in the DC-DC converter. Visibly, the conduction is higher in the SiC counterpart.

6. Enhancement in Motor Output:

The enhancement in powertrain design boosts the output of the motor as well. For any given design of machine, the speed of motor increases proportionally to the DC link bus voltage. The induction motor starting torque is given by [22],

Starting $T_i = \dfrac{3}{2\pi N_S} \times \dfrac{E_2^2 R_\phi}{R_\phi^{\,2} + X_\phi^2}$ (8)

Running $T_R = \dfrac{3}{2\pi N_S} \times \dfrac{sE_2^2 R_\phi}{R_\phi^{\,2} + (sX_\phi)^2}$ (9)

$$\text{Average}\, T_T = \frac{3k^2}{2\pi N_S} \times \frac{sE_1^2 R_\phi}{R_\phi^{\ 2} + (sX_\phi)^2} \qquad (10)$$

- s = slip of the motor
- E_1 = stator voltage or input voltage
- E_2 = Rotor EMF per phase at a standstill
- R_φ = Rotor Resistance Per Phase
- X_ϕ = Rotor Reactance Per Phase
- V = supply voltage
- K = rotor/stator turn ration per Phase

The performance improvement by evaluating these equations and the model of Fig 2 was used to calculate the output power as a function of inverter power loss. As shown in Figure 9, the SiC inverter operates to a higher operating point with a lesser loss compared to Si counterpart.

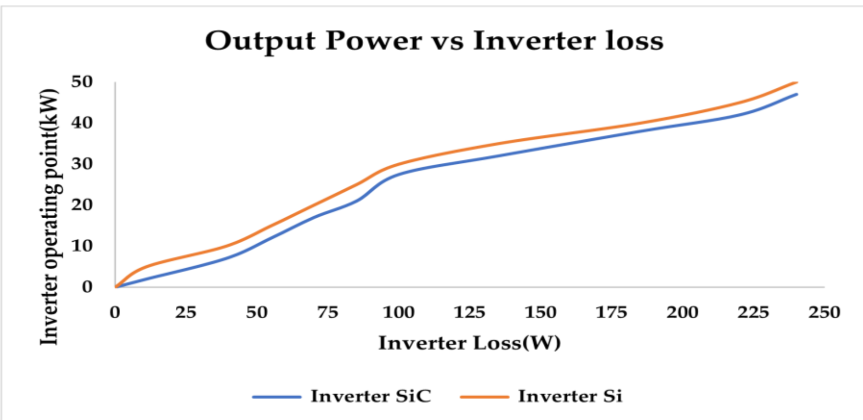


Figure 33 Output Power vs Inverter loss for Motor

7. Mechanical Constraints:

For the same power rating the increase in voltage rating reduces the current ranting. Therefore, the cable cross sectional area reduces [231]. As Ohm's law states, lower current reduces copper loss significantly. But increased number of series conductors are required with increased voltage level in turn increasing phase resistance [20]. A higher DC link voltage can help reduce the copper loss and increase the efficiency [23]. In case of a higher-power motor, the iron loss, mechanical loss, and copper loss will increase with revolutions per minute (RPM}. Along with the thermal constraints the challenge of mechanical loss must be considered. The rotational speed is the square root of the mechanical loss [24]. Improvement in machine structure such as adding notches or thickening the teeth of the motor may be used. However these in turn increase the complexity in machine design in turn compromising the electromagnetic performance due to the modified rotor structure. Therefore a robust motor model suitable for different traction application is highly desirable. However with use of SiC power electronics the stress in motor will be reduced due to lower thermal exposure. Hence all these limitations can be avoided with an 800V SiC design.

8. DCFC:

For the numerical analysis of the fast-charging losses the case study with 400kW for passenger vehicle and 1.2MW for heavy duty vehicle is analyzed. As the conduction losses re lower in SiC, despite having similar voltage level the diode loss is less in SiC. The corresponding current equations for numerical analysis are as follows,

Output current,

$$I_{av} = \frac{P_{out}}{V_{battery}} \tag{11}$$

Average output current,

$$I_{av_1} = \frac{I_P}{n\pi} \quad (12)$$

RMS current of diode,

$$I_{rms} = \frac{I_P}{2\pi} \quad (13)$$

9. Auxiliary Power Unit:

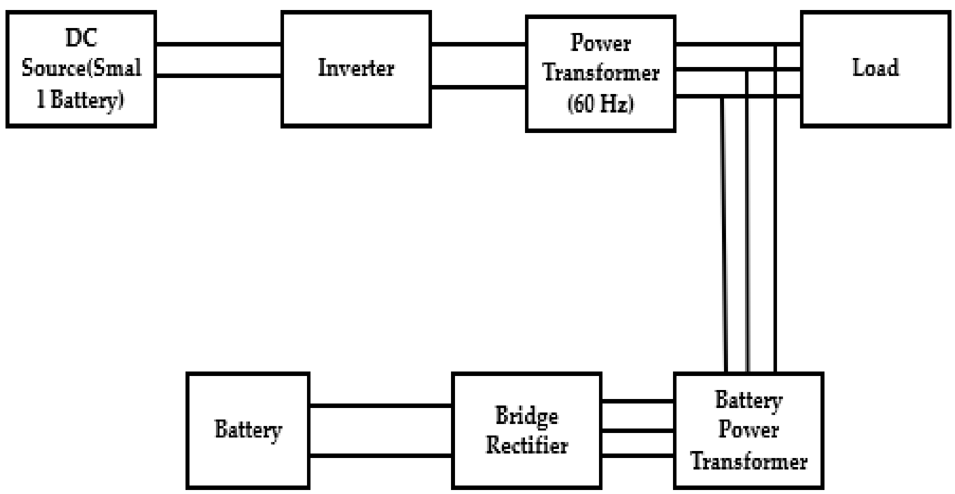


Figure 34 : Conventional APU for Powertrains with bulky transformers and Si Electronics.

Zero-voltage-switching full-bridge, full-bridge center-tapped and Dual active bridge converters are the primary topologies used in auxiliary power converters in APU. The APU controls the battery, motor and regulates the voltage level through converter signals. As the power converter rating increases with the implementation of SiC MOSFET, the need for a component with high enough blocking voltage also arises. Si MOSFETS above 800V is available in market with the tradeoff of cost and high losses. Instead IGBTs can be used but suffers similar problems of high cost and high turn off time. To reduce the weight and size of passive components such as transformers and capacitors a high frequency device must be chosen such as 100kHZ, IGBTs are not suitable for operation above 20kHz. Keeping all these in mind the SiC MOSFETS emerge as a winner [26]. Implementing SiC will reduce the cooling of the APU by using soft switching in the designated power converter.

As observed in Table 1 already, SiC has a 8 times larger breakdown field compared to Si. Thus, a larger breakdown voltage can be applied in SiC device without increasing the on-state resistance. As the thermal conductivity is also 3 times larger the heat dissipation is more. The wide energy band gap stops the electrons to move to the conduction band making the leakage current lower even in higher temperatures. Furthermore, replacing the conventional IGBT structure of APUs with higher switching frequency of MOSFETS the operation range increases. In certainty the overall APU performance increases.

10. Cost of SiC Power Electronics:

All the aforementioned sections give an in-depth look into the high efficiency of SiC and it's potential to replace Si in entire EV structure. However, the low productivity and high cost is a major factor obstructing industry to reap the benefits of SiC. Around 30% to 40% of the cost of the EV inverter pertains to the device used. Hence using a device multiple times higher cost drives the car cost significantly. However, the implementation of SiC will drive down the cost of cooling cost significantly. Thus, reducing the cost. Other than approaches taken during car manufacturing, there are measures to be taken in SiC manufacturing as well. The components of SiC die is abundant in nature, hence, supply chain issues are almost impossible. Government's energy policies in favor of electrification of transportation, volume manufacturing and single wafer processing and large diameter wafer manufacturing are implemented. 200mm fabs increasing from150mm is being adopted. This will help to reduce the feature size and defect density of the transistor. The cost of power electronics will also thus reduce just like the reduction of cost of Si. Analogous to the growth of nanoelectronics and power electronics with the implementation of Si instead of rare earth material, the path to SiC will advance in a comparable way. Cost breakdown of a SiC MOSFET die[6] shows that SiC die manufacturer purchased SiC wafer from the market. On the other the hand, data on the right side shows in-house manufacturing of SiC wafer as well as die [6]. Clearly, the cost lowers when companies volume manufacture in their own facility. Thus the substrate cost, die cost and die size can also be reduced.

11. Simulink Design of a Fully SiC Powertrain:

To validate the findings of the mathematical model a simulation model was done. A Li-ion battery block was chosen from Simscape specialized power systems. It was an 800V battery which is capable of running a multi motor system. A 3 ph neutral point clamped converter is used using the SiC MOSFET Mitsubishi PSF25S92F6-A. The switching control was done akin to the grid tie inverter switching using MPC. The applied method is using the optimal switching sequence (OSS) concept to compute the control action. The system constraints need to be handled like temperature, current limit. Therefore the computational burden needs to be in a certain limit. In many digital hardware platforms this method is implemented nowadays which justified this approach to the authors. OSS applies the switching sequence to the power converter during next sampling period. However, PWM may seem like a more robust and conventional option, but the purpose of this paper lies in the justification of power savings by SiC implementation and the faster switching time and higher current limit of SiC can handle this higher level control algorithm[27]. The load chosen is a fixed RL load.

The switching sequence for 3^3 or 27 switches were manually computed as mentioned in bibliography. Using the forward Euler's method in voltage equation the reference block was created. For a RL load the working equation can be given by

$$\frac{di_s}{dt} = \frac{1}{L}(v_s - ri_s - v_{ab}) \quad (14)$$

The equation uses a for loop and repeats the action for the corresponding switching signal. This code was placed inside a MATLAB function block and the resultant was used as the switching signal for NPC. The switching states can be shown below:

Table 17 switching sequence for the respective legs of the neutral point clamped converter.

M_{1X}	ON	OFF	OFF
M_{2X}	ON	ON	OFF
M_{3X}	OFF	ON	ON
M_{4X}	OFF	OFF	ON
V_{XO}	V_{DC}	0	V_{DC}
Switching States	1	0	-1

Following the switching states as mentioned above the vectors for 3^3 or 27 switching sequences were calculated manually and put into the function block working as the trigger circuit for the Powertrain converter. The switching sequences are mentioned in Table 7.

Table 18 Calculated switching sequence for the proposed model.

Vector	M_a	M_b	M_c
V_0	-1	-1	-1
V_1	0	0	0
V_2	1	1	1
V_3	1	0	0
V_4	0	-1	-1
V_5	0	0	-1
V_6	1	1	0
V_7	0	1	-1

V_8	-1	0	-1
V_9	-1	0	0
V_{10}	0	1	1
V_{11}	0	0	1
V_{12}	-1	-1	0
V_{13}	0	-1	0
V_{14}	1	0	1
V_{15}	1	-1	-1
V_{16}	1	0	-1
V_{17}	1	1	-1
V_{18}	0	1	-1
V_{19}	-1	1	-1
V_{20}	-1	1	0
V_{21}	-1	1	1
V_{22}	-1	0	1
V_{23}	-1	-1	1
V_{24}	0	-1	1
V_{25}	1	-1	1
V_{26}	1	-1	0

The model can be expressed in terms of block diagram from the figure below:

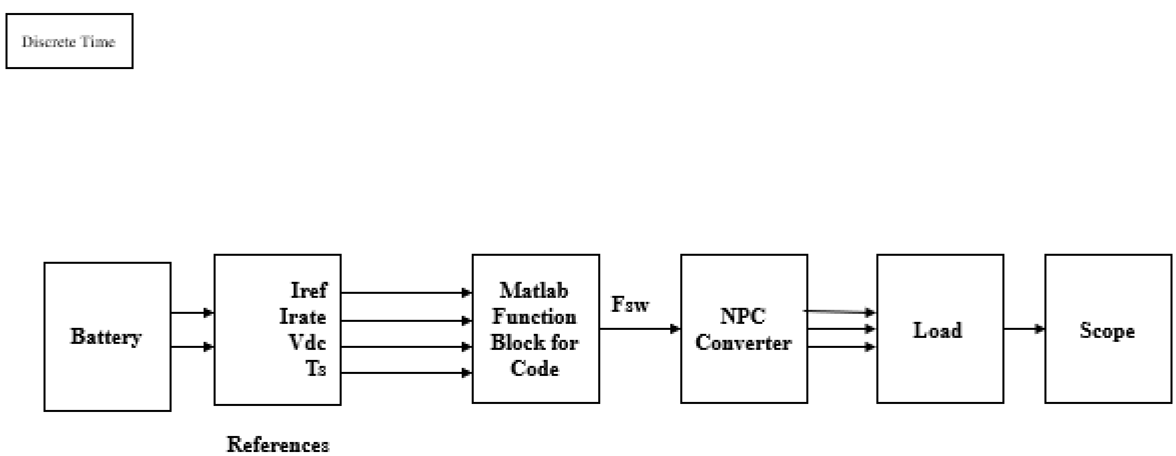
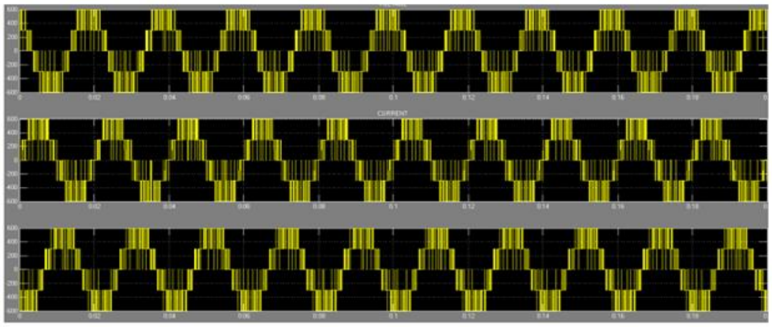
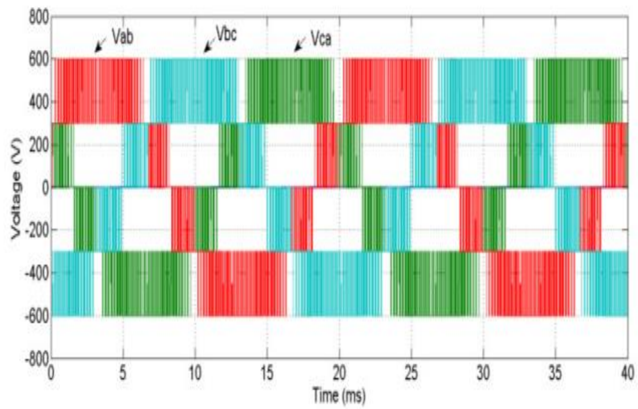


Figure 35 Block Diagram of Developed Simulation Model

The power output for one motor system can be seen below. Another smaller motor can be connected at the battery output as the higher efficiency SiC is wasting less battery power and working at its optimal output level.



(a)



(b)

Figure 36 (a)Simulation result for output voltage of SiC-NPC converter- three separate phases.

11. Conclusion:

In this article we have analyzed the future trend in EVs to completely switching to SiC based power electronics-based power train instead of the current use of Si power electronics for higher voltage levels. A similar 800V Si power train system derived mathematically and by simulation was compared to the SiC power electronics-based system. A thorough step by step analysis for all the components of powertrain was done. The findings show that even with a similar 800V battery the size and mass reduction due to the reduction in cooling components and higher current carrying capability remains significant. The motor of the power train can achieve more RPM under SiC technology. The power electronics will be lighter and heat dissipation will be significantly lower. The chargers will have a robust structure under SiC to enable faster charging in both grids connected and DCFC mode. Even the smaller components as auxiliary power unit will show a stark reduction in size and power density due to replacement with SiC enabled bus. With the cost reduction trend of silicon carbide power electronics, our conclusion is that the power level can be significantly increased to keep up with the ever-increasing capacity of extremely fast charging thus attracting more customers for electric vehicles.

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CHAPTER 5

CONCLUSION

The expansion of electric vehicles made the expansion of charging infrastructure rudimentary to keep up with this developing technology that helps people in a myriad of ways. The main drawback in electric vehicle charging, however, is the time consumed to charge a vehicle. The fast charging of electric vehicles solves this problem thus making it a lucrative technology for consumers. However, the fast-charging technology is not without its limitations. In this dissertation we have identified the technology gaps in EV fast charging stations mostly focused on the extremely fast charging topology. It will help pave a path for researchers to direct their effort in a consolidated manner to contribute to the fast-charging infrastructure. The importance of DC power network based on free fuel energy sources and silicon carbide-based power electronics are proposed to provide ultra-low cost and ultra-high speed XFC stations.

Existing extremely fast charging (XFC) of electrical vehicles (EVs) is based on silicon power electronics and internal conversion of AC power into DC power. This dissertation shows that silicon carbide power electronics and the use of DC power source in the design of XFC of EVs has many distinct advantages over current XFC of EVs. Silicon carbide power electronics provide reduction of charging time, higher power conversion efficiency, size reduction of heat sink and improved battery's state of health. Current networks combined with silicon carbide based XFC of EVs can play a revolutionary role in saving green electrical and provide reduced charging of EVs. Therefore complete swap of Si with SiC and basing the power network on green energy was proposed in this dissertation.

In future, extremely fast charging is the only solution to these problems. But the typical Silicon power electronics supported 400V electric vehicle powertrain cannot live up to this challenge. Limitations include the huge cable size, heating of equipment due to high current and user safety, to name a few. Therefore, this dissertation analyses an 800V EV powertrain using UnitedSiC

UF3C170400K3S. To implement this higher-powered train in vehicles, the complete reconsideration of the electrical system is imperative. Although industry is already using partial SiC. The implementation of fully Silicon Carbide based Power electronics was untouched.

Analysis and simulation based on the architecture of heavy-duty vehicle fast charging and the powertrain in Electrification of Transportation was done in this dissertation. SiC integrated circuits indicate that DC-SiC based heavy duty vehicle fast charging will provide superior performance as compared to their current AC-Si counterparts. Next steps of analysis and simulation proved that only making the charging infrastructure high power was not enough, we need to develop a fully SiC based high voltage powertrain to receive the charging as well. Thorough analysis of performance, reliability, and lower cost of ownership of SiC based heavy duty vehicle fast charging and powertrain is the future of EVs. Proof for future trends on lower cost of manufacturing of SiC based power electronics has been discussed. The advantage of SiC in long and short-term system level development is clear. For EOT, this dissertation was based on an end-to-end DC system (power generation, power storage, power transmission, XFC and powertrain) based on Silicon Carbide power electronics.

In future a fully system level approach for electrification of transportation based on SiC power electronics and green energy-based DC power network will be the scope of the future leg of this research.

APPENDICES:

NOMENCLATURE:

AC	Alternating Current
BMS	Battery Management System
CPS	Cyber Physical System
CHAdeMO	Charge de move
CCS	Combined Charging System
CAN	Controller Area Network
DC	Direct Current
DAB	Dual Active Bridge
EV	Electric Vehicle
ESU	Energy Storage Unit
XFC	Extremely fast charging station
ICEV	Internal combustion Engine Vehicle
ECU	Electronic Control Unit
EPA	Environmental Protection Agency
EOT	Electrification of Transportation
EVCS	Electric Vehicle Charging Station
ESR	Electrical Service Requirement
IGBT	Insulated Gate Bipolar Transistor
kW	Kilowatt
HVDC	High Voltage Direct Current
MW	Megawatt
MVAC	Medium Voltage Alternating current
MOSFET	Metal oxide semiconductor field effect transistor
PV	Photovoltaic
PWM	Pulse Width Modulation
RES	Renewable Energy System
SoC	state of charge
SiC	Silicon Carbide
THD	Total harmonic distortion
V2G	Vehicle to Grid

"It is our choices, that show what we truly are, far more than our abilities"
-Albus Dumbledore

THANK YOU