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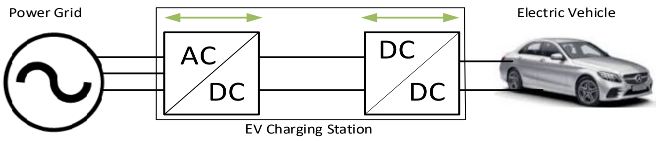
Bidirectional Power Transfer between Grid and Electric Vehicle Batteries



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Summary:

In the last decades, the significant growth of electric vehicle (EV) is promising an alternative to solve the concern about fossil fuel and global warming. However, as the number of EVs increasing significantly, it can cause overload in the existing distribution network of the power system. The vehicle-to-grid (V2G) technology is recognized as the best alternative to mitigate the stress in the electric grid by providing ancillary service and power balancing in the power system. The tasks covered in this thesis are:

Different effective ways of EV charging are reviewed, and their advantage and disadvantages are addressed. A literature review of common bidirectional AC-DC and DC-DC converters are carried out. Several converter topologies can be used to implement the bidirectional EV chargers. It is found that the two-level three-phase AC-DC converter and either half-bridge buck/boost for a non-isolated converter or a dual active bridge for an isolated converter in DC-DC converter are leading topologies. For safe and reliable power transfer between EV and the grid bidirectionally, the available bidirectional charging standard is investigated. Right now, the only bidirectional charger accepted as standard is the CHAdeMO with DC charging. Finally, a two-stage bidirectional EV charger with and without galvanic isolation is developed and simulated in MATLAB/Simulink. The first stage is a three-phase AC-DC converter, and the second stage is modeled with both half-bridge non-isolated DC-DC converter and dual active bridge isolated DC-DC converter. All the converters transfer power bidirectionally. The simulation results showed that the two-way power transfer with the proposed bidirectional EV charging station models is feasible.

Preface

This thesis has been done in the last semester to complete the two years Master's program in Electrical Power Engineering at the Univerisity of South-Eastern Norway (USN). Kjetil Svendsen proposed and supervised the thesis, "Bidirectional Power Transfer between Grid and Electric Vehicle Batteries." The main tasks in this thesis are literature review on converter technology for bidirectional EV chargers, the effective way of charging EV from environmentally friendly energy sources, and investigate the available standard bidirectional EV chargers. At last, to develop a simulation model of a bidirectional electric vehicle charger in two parts separately with and without galvanic isolation in MATLAB/Simulink.

I would like to express my deepest gratitude to my thesis supervisor associate professor Kjetil Svendsen for his guidance, support, and especially for giving me unlimited time.

Porsgrunn, 15 May 2020

Okbe Kifle Habte

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Nomenclature

Symbol	**Unit**	**Description**
AC	-	Alternating current
BPT		Bidirectional power transfer
CCS		Combined Charging System
DC	-	Direct current
DERs	-	Distributed energy resources
EV	-	Electric vehicle
EVSE	-	Electric vehicle supply equipment
f	Hz	Frequency
f_s	Hz	Frequency of the transformer
G2V	-	Grid to vehicle
HV	-	High voltage side of the transformer
$i_a(t),\ i_b(t),\ i_c(t)$	A	Utility time-varying phase currents
i_{DC}	A	Current in the DC side of DC-bus
I_{rms}	A	RMS utility phase current
ICE	-	Internal combustion engine
L_{lk}	H	Transformer linkage inductance
LV	-	Low voltage side of transformer
N	-	Transformer turns ratio
P	W	Real power in AC side of the converter
P^*	W	Reference real power
P_s	W	Real power transfer in the converter
PV		Photovoltaic
Q	Var	Reactive power in AC side of the converter
Q^*	Var	Reference reactive power
PWM	-	Pulse width modulation
SOC	-	State of charge
V_1	V	Transformer low voltage
V_2	V	Transformer high voltage
V2G	-	Vehicle to grid
$v_a(t),\ v_b(t),\ v_c(t)$	V	Utility time-varying phase voltages

v_{DC}	V	Voltage in the DC side of AC-DC
V_{rms}	V	RMS utility phase voltage
		converter
t	s	Time
φ_i	radian	Phase angle
$\varphi_i{}^*$	radian	Reference phase angle
φ	radian	The phase shift angle between the square wave in both terminals of the transformer

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1 Introduction

Concern about climate change and its solutions are among the biggest concerns of governments, media, including individual activists all around the world. The problem of global warming is due to the increase in greenhouse gas emissions by human activities. A large part of greenhouse gas is produced from fossil fuel (coal) energy sources and emission from conventional vehicles with an internal combustion engine (ICEs). Now, almost 30% of greenhouse gas emissions in the USA are produced by the transportation sector. Transportation includes cars, ships, trains, trucks, and planes [1]. Moreover, a large number of EVs are already on china's roads; however, one research study [2] discovered that EVs could account for more than twice the emission of the traditional cars powered by gasoline because of the fossil fuel dominated electric power supply. Therefore, it is essential to replace conventional fossil fuel energy sources with green energy sources, as the number of EVs is growing significantly. The research implies that charging EVs from fossil fuel power supply can not reduce the emission [2].

Additionally, in 2017, the transport sector was producing 27% of the total EU-28 greenhouse gas emission, and the emission from the maritime and aviation are not included. Although the target in Europe is to reduce the emission by two-third in 2050 as a reference of 1990, still the CO_2 released from vehicles raised by 2.2% from 2016 to 2017. The target was set out in 2011 [3]. Hence, replacing fuel cars with EV is a promising option to get a significant reduction in greenhouse emissions, especially EV with vehicle-to-grid (V2G) technology. V2G is the connection of EV and the grid bidirectionally in which power can transfer from the electric network to the vehicle and vice versa. The V2G technology enables the utility to use the EV as backup power by charging during off-peak hours and inject power back to the grid at high demand. The vehicle owners can also get revenue by charging during off-peak and selling the stored energy back to the grid during peak hours. Several countries already implement the bidirectional EV charging system. According to [4], Nissan Leaf is the first carmaker approved by German's electricity grid to apply the bidirectional integration of the grid and EV, and Nissan uses the CHAdeMO charging standard. Furthermore, the International Energy Agency estimates that 280 million EV will be on the road by 2040. According to the chief strategist in Volkswagen, EV batteries are expected to contribute to stabilizing the grid by injecting power back to the grid when the wind and solar power levels are low or not available. By 2025, it is expected 350 GWh of energy storage from EV fleet, and until 2030 it will raise to 1 TWh. That is greater than the total energy generated by hydropower plants in the world today, and it will open a new business in the electric utility [5].

Denmark can also be observed as an example in 2019; they achieved almost 50% of the electricity source in the country from a wind turbine. It increased by 4% from 2017 to 2019, and the country's policy is to reduce emissions by 70% under the 1990 level in 2030 [6]. The fast growth of EVs and the implementation of bidirectional power transfer application can improve power system reliability and stability by storing power during surplus in the EV and provide back to the grid when required.

Even if the number of populations in Norway is small, Norway is one of the top EV customer countries in the world, especially electric vehicles are top-rated in Bergen. Bergen ranked as the first city in the world with a significant number of EVs. It reached 20%, or one out of five vehicles in the city is an electric car. The reason to increase the number of electric vehicles in Bergen could be another than the environmental concern. One of the biggest motivations for the people in Bergen for shifting from conventional to the electric car is the discount on road tolls payment for EVs is considerable. However, it is playing a significant role in reducing carbon dioxide emissions. People in Bergen may be motivated by money, but the politicians reach their goal by cutting toll on roads and tax on EVs. Cities like Bergen calls for a bidirectional charging for integrating the EV with the grid to benefit the large number of EVs [7].

1.1 Background

Currently, most of the countries are aiming to achieve zero-carbon dioxide emissions from electric energy production, transportation, and other industries. When it comes to electric energy sources, it is essential for providing environmentally friendly, reliable, and economical electricity for customers. However, it is complex to predict and may not be possible to dispatch some renewable energy sources due to the random variation of their availability. For example, electric supply generating from solar power profoundly affected by the sunshine and the wind turbine also depend on by the blowing of the wind. That means the renewable energies may have a surplus or insufficiency of power generation at certain times. For instance, solar panels may have excess electricity in the day time when it is sunny, and this excess energy will be wasted if the producing energy is more than consuming energy by the load and if there is no storage. On the other side, the production power at night and cloudy weather will reduce significantly, and at this time, the power system requires support from stored energy. However, if there is no storage system, power may need to be generated by non-renewable energy sources. Similarly, the intermittency of wind energy depends on the blowing of the wind. When the wind is blowing, power can be harvested from the wind turbine, and at this time, if there is excess energy, it is required storage to save energy from wasting. On the other hand, there comes a time with no blowing wind results in no energy production, which needs to use from stored energy or other energy sources. Additionally, the loads in the residential, industrial, and commercial fluctuate constantly. Furthermore, the growing number of EVs on the roads induces an additional problem on the power system stability. The EVs are an extra load to the existing electric distribution infrastructure. Therefore, an expensive bulk of batteries is necessary to overcome all the issues stated above. Instead, there is a trend toward using the parked EVs as a distributed energy storage system using V2G technology. The EVs charge when there is low demand in the grid, and discharge to the grid on peak-hours to balance generation and consumption in the grid. EVs with bidirectional connectors decrease the impact of the variability in the production of renewable energy sources by acting as load and distributed energy sources [8].

As the number of EVs growing fast, the deployment of DC fast charging is also increasing to avoid EV customers' anxiety waiting for charging their vehicle. The DC fast charging draws a high amount of power in a short time, and this causes an additional challenge to the grid. However, this issue can be changed to positive by bidirectional integration EVs with the grid for providing electric providers and EV owners economic benefit and also solve the technical difficulties in the grid [9]. The two-way power transfer is the concept of the smart grid, and the EVs can respond immediately with a large amount of power if there is a sudden unbalance between supply and demand in the power system [10]. Furthermore, looking for an efficient way of charging an EV for electric utility and vehicle owners' benefit is essential. For supporting electric utility, EVs should charge when the electricity generation from intermittent energy sources is high. From an EV owners' perspective, charging a vehicle where the power source is cheapest is a valuable way of saving charging expenses, such as comparing charging at home and commercial charging stations. So, by a little bit of planning and charging as much as possible when the source is cheap, EV owner can reduce charging costs [11].

A vehicle fleet and EVs owned by individuals parked most part of the day, and during this idle time, they are plugged into the grid. So, at this time, the EV battery can provide emergency support to grid stability if there is fluctuation in production or consumption in the power system. For example, it gives frequency regulation in the grid by regulating charging and discharging of real power. In this scenario, the EVs battery is used as a distributed energy resource and load. As the EVs can be considered as energy storage, it is expected to contribute to the increasing installation of environmentally-friendly electric energy sources, like wind and solar power. The smart bidirectional integration of several EVs and the grid is anticipated to play a significant role in renewable energy dominated electric power sources like in Denmark[9].

Presently, EV charging stations are available everywhere. However, the possibility of energy flow is only one way from the grid to the EV battery. Most of the EV companies are working extensively to provide a bidirectional charger. By employing the proper and efficient converters, it is feasible to distribute the two-way power transfer integration of EVs and the grid. According to numerous researches, there are various ways to implement the bidirectional charger. DC fast charging is found to be superior for different reasons. One of the first reasons is charging a vehicle in a short time, and providing sufficient immediate power from the EV to the grid can increase power stability [12]. Implementing this two-way power transfer with smart integration can help to fully electrification of the transport sector to reduce peak hours stress in the distribution part of the grid. Also, EV owners decrease charging costs by contributing power to the grid[9].

There are many parties interested in benefiting from the development of vehicle-to-grid technology. Some of them are vehicle manufacturers, vehicle battery manufacturers, vehicle owners, EVSE owners, the aggregators (service providers), homeowners, and electrical utility. In residential utilization, vehicle owners, EVSE owners, and homeowners belong to one. When it comes to commercial systems, more participants are probable. The utility has several advantages from V2G technology; two of them are the following. The first is to use EV as storage, and give load-leveling for intermittent renewable energy sources. The second is providing ancillary services for the grid when it needs from the stored energy. The ancillary service is providing power immediately for the grid in case of a power system equipment failure or outage. As mentioned earlier, the adoption of renewable energy sources like solar and wind is increasing, and they are not consistent. The probability of coinciding the peak hours and production time is also less. However, the EV connected with the bidirectional charger plays a significant role in increasing the efficiency of variable renewable energy sources [13].

In a V2G system, informed and a willing vehicle owner is a key to implement the system. The vehicle owners want the car ready whenever they need to drive it. However, the owners should understand the primary contract that they agreed with the electrical utility. Another concern from vehicle owners is participating in grid support can cause battery degradation, and it lowers the life of the battery. However, the design of smart EVSE with programming maintains at a particular state of charge (SOC) can avoid battery depleting. If the participants are well educated about the system V2G technology, they can get significant benefits by employing their vehicle as a battery storage system [13].

Furthermore, another entity is required called aggregator in the energy market to obtain successful integration V2G technology economically and technically. The aggregator works as an intermediate between the EVs and electric utility. The aggregator has information about how many EVs are connected to provide power to the grid and state of the grid. The aggregator is responsible for delivering a daily demand forecast for the EV owners to know the best charging time and when there is an energy request from the utility. This information must be approved by the Distribution System Operator (DSO) before providing to the EVs owners[9] [14].

1.2 Objective and Scope

The foundation for this study is implementing bidirectional power transfer between EV and the grid to get environmental and economic benefits. The tasks of this study are to survey efficient EV battery charging from renewable energy sources, to look over the converter technology for bidirectional power transfer, to review standard for bidirectional EV charging. Lastly, to develop a two-way EV charging simulation models with and without galvanic isolation.

The number of EVs is increasing rapidly, and the electricity generation is also in good trend in the transition to carbon-free energy sources. However, to match the available renewable energy with the demand for charging EVs is crucial to make EVs greener. Different approaches can be used to charge EVs only from carbon-free sources. The fastest-growing renewable energies are wind and solar power, so the EV charging should be managed based on the availability of these sources.

Renewable energy sources are expanding rapidly, and the intermittency of renewable energies cause to raise the importance of the energy storage system. The energy stored in the battery during low demand should discharge back to the grid when the renewable energies are not available. To realize the energy storage and bidirectional power transfer, exploring of converters with the ability of two-way power transfer is a critical factor in the system. A bidirectional AC-DC converter is a fundamental requirement for the energy storage system and two-way power transfer between the EV and the grid. According to the application, different types of converters can be used. A bidirectional DC-DC converter is also essential in some cases for additional voltage regulations. Furthermore, the two-way DC-DC converter classifies in to isolated and non-isolated based on the galvanic separation between the AC source and energy storage battery.

As mentioned earlier, to reduce carbon dioxide emissions to the air, the electrification of the transport sector can play a significant role. The increasing number of EVs can be both challenging and advantage to the power system. By controlling charging patterns, the negative impact of EV on the power system can be reduced. Another vital issue to be considered is the standard connector for charging and discharging EV. Two important reasons to use the standard connector are the connector should be approved by the manufacturer for EV battery health and to comply with the regulation of electric utility when power is injecting from the battery to the grid.

The last objective of this study is to develop simulation models of a bidirectional EV charging station in Simulink/MATLAB. The simulation model consists of two stages of conversion. The converters used for the two-stage structure of conversion are three-phase AC-DC joins the grid and DC-bus, and DC-DC converter connects the battery with DC-bus, and both operate bidirectionally. The charger is to be modeled with a non-isolated and isolated DC-DC converter. The non-isolated converter is a half-bridge (buck/boost), and the isolated converter is a dual active bridge. Only active power is transferred in both directions to charge the EV battery and to maintain the grid frequency stability.

To summarize, the rest of the report is organized as follows: Section 2 presents a survey of a different effective way of charging the EV, while section 3 shows a review of some common converter technologies for bidirectional energy transfer. Part 4 provides the investigation of the available EV charger standards for charging and for bidirectional operation. In parts 5 and 6 are developing a two-way EV charger simulation models with and without galvanic isolation, respectively, in MATLAB/Simulink. Finally, the last section presents the conclusion of all the tasks.

2 Efficient EV Battery Charging

Awareness of the impact of a large amount of carbon dioxide emission from the traditional internal combustion engine (ICE) vehicles, prompts to increase the electrification of the transport sector. Charging EV from the conventional energy source produced by fossil fuel will not reduce the emission of carbon dioxide, which is merely switching the emission instead of from the EVs to an energy source power plant. The number of EVs all around the world is growing at an unprecedented rate, and this will increase electric demand. Therefore, it is very timely for both EV owners and electric utilities to find a new way of charging EV from a reliable and environment-friendly energy source to reduce emissions and to save charging costs [15].

2.1 Literature Review

The power consumption by EV is a notably large amount. The power demand of one household in Europe is comparable to Nissan Leaf with a 24kWh battery pack. Consequently, it can increase the current energy demand from 17% to 25% with growth in the number of EVs. Despite all the positive sides of the EVs in the environment, they can cause a significant and unavoidable negative impact in the power system if the electrification of the transport movement continues in the same trend without considering the power system[16]. As the number of EVs on the roads is increasing, discovering an efficient charging way is required. In this section, an overview of the technical and economically efficient way of charging the EV battery alternatives will be presented.

Installing photovoltaic (PV) is possible in most of the places, including in cities, unlike other power sources, highly dependent on position. As PV is an environmentally friendly source, it can be used to charge EV directly with DC connector. In one research paper [17], they proposed integrating of charging station with a solar power plant with battery storage and grid can provide sustainable power for EV charging off-grid or grid-connected. The approach for this system is charging the vehicle from the PV is the first option, and if there is uncertainty about PV at night or cloudy day, the storage battery takes as a secondary option. During adverse conditions, the grid secures charging at any time. The storage battery should be kept fully charged all the time, and it can also charge from the grid during off-peak hours and use during peak hours to charge the EV if the PV is not available at that time. The system is beneficial both to EV owners economically and technically for the electric utility. The EV owners, by investing in the photovoltaic and extra storage battery, they can save money on charging, and also installing photovoltaic for charging EV reduces the load in the distribution of the power system. Besides, the extra storage battery supports the utility for power system stability by charging during low demand and avoiding connecting during high power demand.

Several numbers of research have been done to explore optimal EV charging strategies, for example, smart charging. The smart charging may define in different ways, but it is a strategy of charging EV by which charging patterns change according to the demand of electrical energy. Three scenarios to apply smart charging are as follows [18]:

- Peak shaving scenario: Charging EV during off-peak hours or spreading the charging time of vehicles in the same area.

- Renewable energy scenario: Charging EV when the availability of renewable energy is high as much as possible, like wind and solar.
- Balancing scenario: By varying charging patterns keeping the balance between demand and supply in a power system.

Furthermore, the smart charging can also be classified in two as unidirectional and bidirectional. As mentioned above, with unidirectional charger, it is possible only to charge or disconnect the EV based on the demand in the power system, and the bidirectional charging (V2G) has the additional advantage of exporting power back to the grid from the EV battery. In the research paper [19], smart charging is defined as intelligent control methods for charging. The charging control divided into two as centralized (direct) and decentralized (indirect) control. In centralized control, the charging power of EV is decided remotely by the aggregator. However, in the indirect control method, the EV owners decide in response to the information they receive from the electric utility or aggregator. The charging control is prepared based on the optimization approaches to increase power system stability and satisfy EV owners [19].

San Diego firm Envision Solar is the world's first company developed completely solar-powered off-grid and mobile EV charging station. They called it Electric Vehicle Autonomous Renewable Charger. Envision Solar International Inc is a San Diego based sustainable technology innovation company. The charger is designed in the size of one car parking, as shown in Figure 2.1, and it can produce around 6000kWh of power per year, and the system has an energy storage of 21.6kWh, which can be used at night [20]. Its mobility and no installation work make attractive this solar charger. The charger produces 18 to 25% more power than fixed solar energy, and it is estimated to charge 150 miles of EV per day, and this distance is far from people they need to drive on a regular day [21]. It doesn't require great weather for solar power to work. The weather in Germany is rainy, gray and cloudy, but the highest concentration of photovoltaic is in Germany. Accordingly, solar can operate effectively in most parts of the world [22].

Figure 2.1: Stand-alone solar energy EV charging station [20].

The work in [23], proposes installing solar power at the workplace is an excellent strategy to charge EV efficiently. Most of the people work in the daytime, and solar production is maximum in the middle of the day. Furthermore, there is no probability of interruption charging, as most people work continuously for eight hours. The study showed that in this way, EV battery charges cost-effective, and it can be injected to the grid when there is an unbalance between supply and demand [23].

The significant development of renewable energy like solar and wind energy provides a possibility to charge EV from the hybrid power plant. The hybrid power arrangement is two or more energy sources that supply power to the charging station. The hybrid infrastructure is more advantageous in rural areas with limitations to access the utility. Some energy sources fluctuate with the weather, but this can cause a problem if the energy source is one. Solar panels produce low energy during a cloudy day or at night, while wind power plants depend on blowing of the wind, and it is windier at night, which is reverse to solar energy. Hence, the probability of exciting at least one source is high, where when one power supply is unavailable, and the other is available. The hybrid infrastructure provides a reliable energy source, and the availability of power anytime can realize efficient charging of EV, and as a result, the distribution of EVs increase [15] [24].

A wind-solar power station developed by Sweden-based energy company called Innoventum can charge EV, power home, and it can also connect to the grid. It is made up of a wooden structure to hold 24 solar panels and a wind turbine attached at a 12-meter height pole, as shown in Figure 2.2, and its name is called Giraffe 2.0. The hybrid power station can produce 13.8 MWh per year and almost 38 kWh per day. The combination of solar and wind makes it reliable, so the system is expected to provide electricity consistently, but the amount of generation may vary from time to time. The system can be used for different applications, and if it is used only for charging EV only, it can supply an EV charging station with a 50 kW DC-fast charger or two level-2 charging connectors. Even if the system is expensive, about 55,000 Euro, it is a useful solution for remote areas that have no access to the grid. The Giraffe 2.0 system is already installed in Sweden and other parts of the world [25].

Figure 2.2: Giraffe 2.0 hybrid (solar-wind) stand-alone power supply system [25].

In the past several years, the price of solar panels has dropped, intending significant growth in the installation of solar power. Silicon is the crucial element for the construction of solar panels. Researchers have been working extensively to make the solar panel more cost-effective. However, the price of silicon increased due to a lack of supply in the market. In one recent research [26], addressing the shortage of silicon can be enhanced by reducing the thickness of silicon in the photovoltaic cells. Now, the thickness is 160 micrometers, and this can be lowered to 100 micrometers still works efficiently. This reduction is possible to be done by the available technology, but a further decrease in thickness may require new development in technology. This reduction plays a vital role in price reduction and the distribution of the manufacturing of solar panels. Another research [27] shows that traditional silicon solar cells can be replaced by cadmium telluride (CdTe). This material is similar to a silicon solar cell in its efficiency, but cadmium telluride operates better at hot and cloudy weather. Also, CdTe is 10% cheaper than silicon solar in the present market. According to these researchers, the charging of EV from a solar power plant will be efficient, and it will play a significant role in reducing the stress in the distribution part of the power system due to the increased number of EVs with bidirectional connector.

For people homeowners, by investing in installing renewable sources such as solar and wind power at home, they can avoid EV charging costs. Even if the power is available when it is shine or windy, by charging during the excess power available and discharge to the grid by connecting with a bidirectional charger in the charging station, the utility will pay them for the contribution. Indeed, charging EV from solar or wind is the most cost-effective and environmentally friendly nowadays [11].

By installing solar panels on the roof at home, power can be fed to the grid during the production of excess energy more than all the household appliance consumes. However, the revenue to supply power to the utility is not satisfactory in several countries, and there are some technical criteria to comply with for providing electrical power to the grid. The technical requirements are voltage regulations, power factor response to frequency change or short circuit in the grid, reactive power supply, and also the amount of power exporting. Instead, it would be better to store the excess energy in the EV when the sun is shinny to use it when the sunsets to power home. The modern EV battery is good enough to power all the households for several days. The EV battery is operating as energy storage, and the concept is the same as V2G, which is called vehicle-to-home (V2H) [28].

V2G system is an EV charger with bidirectional power transfer functionality. In the Netherlands province Utrecht, a world-first smart solar power charging station for EVs with the technology of V2G tested in 2015. Twenty-two charging stations with the capability of charging and discharging installed throughout the province and almost 40 EVs participated in the system. The EV owners were told to charge their cars when the solar is producing abundant, and they have to connect with a bidirectional charger to the grid to supply the unused energy when renewable energy is not available. Each customer was able to save an average of 131 to 820 Euros per year. Based on the result, the program was satisfactory, and they announced that 1000 additional chargers with V2G functionality and 10,000 solar panels are expected to be installed [29].

2.2 Discussion

The literature reviewed in this section helped to investigate the latest trends in technology emerging recently for effective charging of EV from environmentally friendly energy sources.

EVs become green and eco-friendly only if they charge from the emission-free energy source. The several approaches used to make EV charging economical and environmentally friendly are discussed here.

EV charging station integrated with solar power, additional storage battery, and the grid can provide sustainable, eco-friendly, and cost-effective electricity for charging the vehicle. The system applies to commercial or public charging stations to ensure power system stability and reliability. Also, if the system is installed with V2G bidirectional capability in the workplace, it would be more beneficial for both customers and electric utility. The workplace is the longest time people can park their cars outside their homes. However, this application is expensive for individuals to implement in residential due to the extra cost of the photovoltaic and storage battery.

Another essential consideration is that to establish a managed charging system when renewable energy is not off-grid. If the grid is not entirely renewable energy, to develop a system encouraging customers to shift charging times and offering a special discount at a time with abundant renewable energy generation is essential to balance supply and demand. For example, solar is ample during particular daytime, and the wind is abundant at night. The system can be implemented to charge the vehicle either when high renewable energy generation or during off-peak hours.

EV can be used well beyond the means of transport as battery storage for intermittent energy sources such as wind and solar. The main advantages of the bidirectional V2G application are the following: The variability of renewable energy sources can be improved by using the EV battery as a battery storage system and discharge to the grid when it is required. Generation and load balancing in a power system are possible by valley fillings and peak load shaving. Valley filling, in this case, is charging EV at off-peak hours like at night and avoid charging during peak hours and provide power from EV to the grid when it is possible. Peak load shaving is stopping charging EV quickly if the power consumption spike, which is also called load shedding. If all these are correctly applied, it gives economic benefit for EV owners and electricity providers.

Charging stations powered only from renewable energy like Giraffe 2.0 is power from solar and wind, and San Diego firm Envision Solar are one of the best ways of charging EV regardless of the initial price.

3 Bidirectional Converter Technology

According to several researchers, the traditional converter topologies for EV chargers have only one stage front-end AC-DC converter, and the DC fast charging includes back-end DC-DC converter for better voltage regulation [30]. Similarly, the bidirectional EV charger has two interfaces of power converters to provide the possibility of connecting a variety of vehicles with different voltage levels with one connector. The first stage operates as a rectifier during battery charging. Alternately, it works as an inverter when power transfer from the battery pack to the AC mains. The second stage is the DC-DC converter step down the voltage to the required voltage level for the EV battery during charging and boost the voltage supplied to voltage source inverter during power sourcing to the grid.

Recently the bidirectional power flow from the grid to EV battery and the other way around is getting more attention. The bidirectional converters are the main foundation for vehicles to contribute as a mobile energy storage system. By utilizing the charger with the ability to transfer the power two-way, the EV can be used well beyond the means of transport as battery storage for intermittent energy sources, which charges the EV battery and discharge to the grid with the same connection. To achieve this bidirectional power integration, it requires intelligent and complicated converters with an advanced control system [10]. The EVs are employed as a distributed battery energy storage system (BESS) in the power system. To realize these converters, among the essential considerations, are size, weight, power density, reliability, efficiency, cost, control type of the converter, and so on [31].

With the advancement of semiconductor technologies, researchers have been working extensively on bidirectional converters. The topology of converters can generally be full-bridge or half-bridge. Half-bridge converters are characterized by a few switching components, lower cost, and excellent performance, although there is stress in the elements. Conversely, in full-bridge converters, the price rises with the number of components increase, but the stress in the devices decreases [31]. Metal-Oxide-Semiconductor-Field-Effect-Transistors (MOSFETs) and Insulated Bipolar-Transistors (IGBTs) with anti-parallel diode are the most famous in the power switching converter because of the ability of bidirectional conduction, and higher frequency capability. The converters used in the EV charger for two-way power transfer are bidirectional AC-DC and DC-DC converters. This part reviews the leading converter technology used in the application of V2G technology [32].

3.1 Bidirectional AC-DC converters

The power transfer in the bidirectional AC-DC converter classified into two modes of operation. When the conversion is from AC to DC, it is known as rectifier mode, and during DC to AC conversion, it operates as an inverter. Both the rectifier and inverter mode are used in unidirectional power flow application. The current flow in both directions realizes the two-way power transferring in the converter. Either IGBTs or MOSFETs can be implemented in switching the converter based on the applications to ensure the bidirectional conduction.

Historically, the grid-connected bidirectional converter is developed from the front-end PWM rectifier to supply power from the mains to DC machine drives. Conversely, during regenerative braking, the inverter mode is used to provide the power back to the grid instead of wasting it. Both rectifier and inverter mode have the same control method, PWM. However, when power is to be injected into the grid from regenerative braking or other renewable energies, it requires better power quality to provide the utility by applying such as filters and a better control system. The control of the AC-DC converter should operate in such a way that the phase voltage of the power system should not be affected by charging the EV or providing back power to the grid from the EV battery. Converters with diodes and thyristors introduce harmonics to the grid, but converters controlled with PWM increase the power factor result in raising real power transfer and improve the current harmonics [33]. The bidirectional AC-DC converter can be implemented with a single-phase and three-phase.

3.1.1 Single-Phase Bidirectional AC-DC converter

Single-phase ac-dc bidirectional converter is broadly used in different applications, such as load connected to the grid and distributed energy resources (DERs), EV connected with bidirectional charger, and uninterruptible power supply (UPS). When the AC-DC converter is integrated with the grid, there are several requirements to be satisfied like low distortion line current, power factor correction factor, high-quality dc output voltage, and efficient bidirectional power transfer capability [34]. In single-phase AC-DC converter, half-bridge, and full-bridge topology can be used. The half-bridge scheme experiences higher components stress, but fewer components and lower cost [30].

In [34], the proposed single-phase AC-DC bidirectional converter is deployed in a DC load to interface the grid, and the load is connected directly to the distributed energy resource (DER), as shown in Figure 3.1. The microgrid is dc source, and if there is a surplus in the DER, the converted works as an inverter to supply energy to the utility. Conversely, when power is lacking in the DER, the converter rectifies to provide power the load from the grid.

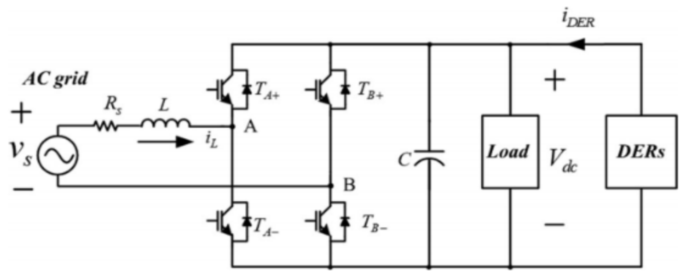

Figure 3.1: A bidirectional single-phase ac-dc converter in a load connected to dc microgrid and the grid [34]

A simplified PWM strategy is employed for switching the converter in Figure 3.1. The simplified PMW approach uses one-fourth of the traditional bipolar PWM and unipolar PWM in the number of switching. During the switching event in the simplified PWM switching, it needs only one switch to change the status. Whereas, in the unipolar PWM or bipolar PWM demands four switches to change the state during the switching time. Consequently, the switching losses reduce significantly in the simplified PWM switching, and it has higher conversion performance. Also, a feedforward control strategy is used to switch between the inverter mode and rectifier mode shown in Figure 3.2. The simplified PWM switching method has higher efficiency than bipolar PWM and unipolar PWM, and lower total harmonic distortion than bipolar PWM [34].

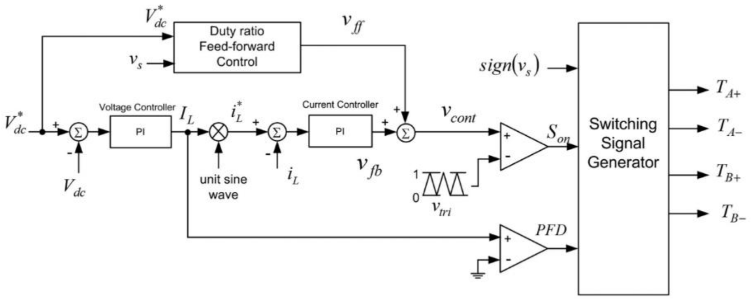

Figure 3.2: Control scheme for the simplified PWM switching [34].

3.1.2 Three-Phase Bidirectional AC-DC converter

Similar to the single-phase, a three-phase AC-DC converter is used in different applications in addition to bidirectional EV charger, such as uninterruptible power supplies, motor drives, grid-connected renewable energy, and battery storage system [33]. The bidirectional power transfer V2G has become essential, particularly in the off-board charging. Very often, the off-board charging station is connected to three-phase power. For an effective bidirectional electric energy transfer between the EV and the grid, a three-phase two-way AC-DC converter is selected as it can handle higher power than a single-phase converter. The higher power handling is essential for quick charging and fast response when the grid needs support from the EV battery with a bidirectional charger. Also, the EV battery is accessed directly by the off-board charging because the converter is in the charging station outside the vehicle. However, the converter is inside the car for an on-board charger. There are several three-phase topologies used for bidirectional converters. Hence, the investigating of different available converters is very crucial to get an efficient converter. Among the required factors are power quality with low THD, high power factor, a low ripple in DC side current, and low distortion in the AC voltage and current [35].

If power MOSFET is used in a three-phase converter, it can cause converter failure due to the inherent MOSFET's body diode conduction. IGBT also has higher conduction and switching losses than MOSFET. Besides, IGBT operates at a lower switching frequency comparing with MOSFET. However, with the evolution of technology, power MOSFET has been used in high power transfer by making the MOSFET’s drain-source on-resistance ($R_{DS(on)}$) extremely low. Hence, switching applications with the MOSFET has very low conduction losses, small switching losses, and higher efficiency [33].

For grid-connected converter bidirectionally, it is assumed that the phase voltage and current of the grid are not influenced by the power transfer to or from the battery. The utility time-varying phase voltages for the three-phase system for the given RMS phase voltage (V_{rms}), frequency (f), and time (t) are expressed as follows below from equation (3.1) to (3.3) [10].

$$v_a(t) = \sqrt{2}V_{rms}cos\ (2\pi ft) \tag{3.1}$$

$$v_b(t) = \sqrt{2}V_{rms}cos\ \left(2\pi ft - \frac{2\pi}{3}\right) \tag{3.2}$$

$$v_c(t) = \sqrt{2}V_{rms}cos\left(2\pi ft + \frac{2\pi}{3}\right) \quad (3.3)$$

The time-varying phase currents for the three-phase are also expressed as follows below with a phase angle shifted φ_i from the voltage.

$$i_a(t) = \sqrt{2}I_{rms}cos\,(2\pi ft + \varphi_i) \quad (3.4)$$

$$i_b(t) = \sqrt{2}I_{rms}cos\left(2\pi ft - \frac{2\pi}{3} + \varphi_i\right) \quad (3.5)$$

$$i_c(t) = \sqrt{2}I_{rms}cos\left(2\pi ft + \frac{2\pi}{3} + \varphi_i\right) \quad (3.6)$$

Where:

V_{rms}	RMS utility phase voltage [V]
I_{rms}	RMS utility phase current[A]
f	frequency [Hz]
t	time [s]

It is clear from the voltage and current showed above, the real power P provided to the grid is given in watts W, and the reactive power is given in volt-amper reactive (Var).

$$P = v_a i_a + v_b i_b + v_c i_c = 3I_{rms}V_{rms}\cos\,(\varphi_i) \quad (3.7)$$

$$Q = 3I_{rms}V_{rms}\sin\,(\varphi_i) \quad (3.8)$$

The apparent power S in volt-amperes is also expressed as:

$$|s| = (P^2 + Q^2)^{1/2} = 3I_{rms}V_{rms} \quad (3.9)$$

The proper control of the real power P and reactive power Q provided by EV battery gives frequency and voltage regulation in the grid. The real power is responsible for frequency regulation, and reactive power is for voltage regulation. The frequency in the grid can raise by providing discharging power from the battery or decrease by charging the battery using the bidirectional charger. The reactive power is not necessary to provide by EV battery if the grid requires reactive power support for voltage regulation in an inductive load. The capacitance in the DC-link is large enough to provide Var [10].

The phase angle ${\varphi_i}^*$ and the efficiency of the converter is expressed as:

$$ {\varphi_i}^* = tan^{-1}\left(\frac{Q^*}{P^*}\right) \tag{3.10} $$

$$ \eta = \frac{P}{i_{DC} v_{DC}} \tag{3.11} $$

The equation (3.11) determines the efficiency of the bidirectional AC-DC converter during inverter mode, and it is clear from equation (3.10) that when the phase angle, φ_i between voltage and current is 0° or 180°, for transferring only real power.

Where:

P	real power in the AC side of the converter [W]
P^*	reference real power [W]
Q	reactive power in the AC side of the converter [Var]
Q^*	reference reactive power [Var]
${\varphi_i}^*$	reference phase angle [radian]
i_{DC}	steady-state current in the DC side of AC-DC converter [A]
v_{DC}	voltage in the DC side of AC-DC converter [V]
S	apparent power [VA]

A three-phase two-level H-bridge bidirectional AC-DC converter is an elementary and simplified topology in the three-phase converter, which is shown in Figure 3.3. This converter has a simple control arrangement and cheap components. However, the current flow concentrates on a few devices, which lead to concentrated losses either in the top or bottom switches. The converter uses IGBTs when the voltage reaches up to 1200 V range, and MOSFETs are also popular in this topology [36].

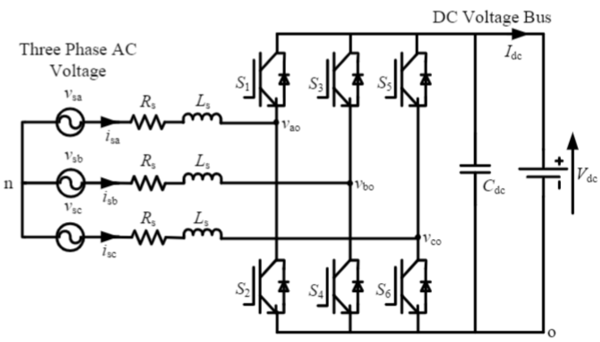

Figure 3.3: Three-phase two-level H-bridge bidirectional three-phase AC-DC converter [38].

Three-phase four-leg converter is presented in [33], as shown in Figure 3.4. The neutral line is used to balance the three-phase outputs. The size of the capacitor and the passive components are smaller than the two-level H-bridge converter in this topology. However, as the number of switches increase, the control gets complicated.

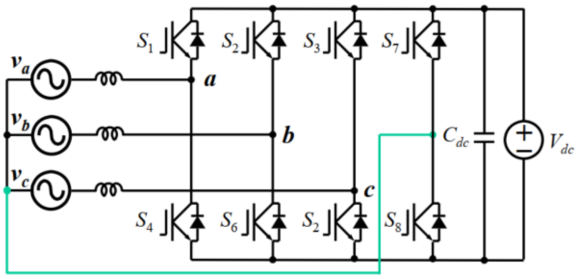

Figure 3.4: Three-phase four-leg bidirectional AC-DC converter [33].

Another topology of the bidirectional AC-DC converter is a three-phase three-level neutral point clamp (NPC). As can be seen in Figure 3.5, multiple switches arranged one over another that benefits to fold voltage link, which decreases the importance of filter. In this topology, low rating switches can be used to give the same operation with the two-level H-bridge converter. It is clear from the structure that to control this converter is more complicated than the two-level H-bridge converter shown in Figure 3.3 due to the increased number of switches. However, the increased level has advantages to reduce total harmonic distortion, gives higher power quality, ripple-free, and regulated DC voltage output is not aggressive to supply and load disturbances [30] [37].

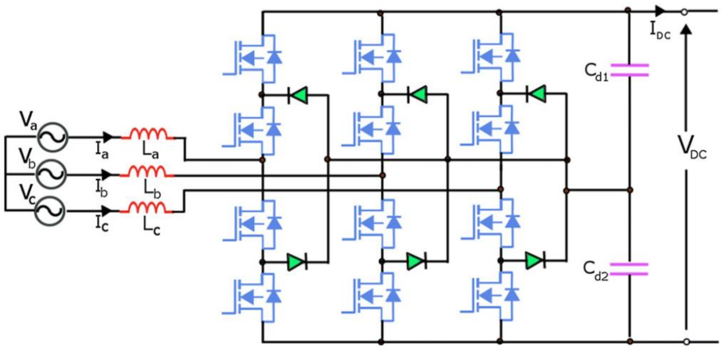

Figure 3.5: Three-phase three-level neutral point clamp AC-DC converter [30].

A single-stage bidirectional AC-DC converter can be used in a two-way power transfer to connect the battery with the grid. The DC link of the converter is directly connected with the battery. Still, the capacitor should be large enough to provide a constant voltage for the battery during charging and to supply regulated voltage to the voltage source inverter during discharging to the grid. The positive side of this topology is, it excludes the DC-DC converter, which is less complex, smaller size, and cheaper. As shown in Figure 3.6, six switches IGBTs with anti-parallel flyback diodes with proper controlling are used for the AC-DC conversion. The PWM technique is used to manage the gates signal of IGBTs. The drawback of this topology is the switches conduct when the gate is off. The transition between on and off causes considerable losses due to high switching losses in IGBT [10].

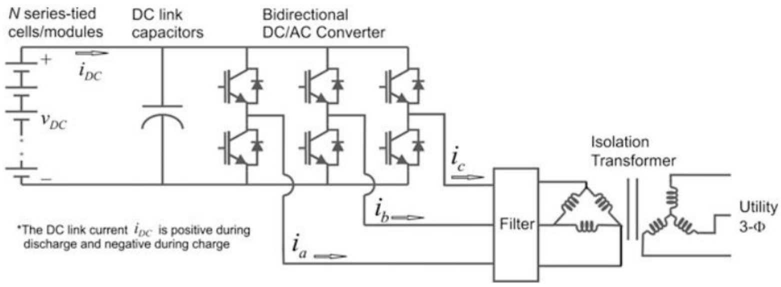

Figure 3.6: Single-stage three-phase bidirectional AC-DC converter [10].

3.2 Bidirectional DC-DC converter

A DC-DC converter is an electronic circuit used in different applications to change the voltage from one level to another in a DC form. With increasing the demand for renewable energy, the importance of a bidirectional DC-DC converter is expanding as the implementation of the batteries for storing energy, and sourcing energy to the grid is required. The DC-DC converter is necessary for the two-way power transfer for additional voltage regulation during the battery charging/discharging, which provides flexible voltage regulation between EV battery and the DC-bus. In some applications, further regulation is not significant. However, in the bidirectional EV charger, both bidirectional DC-DC and AC-DC converters are required [10]. There are many applications of bidirectional DC-DC converters, such as battery charger, hybrid EV systems, UPS, fuel-cell hybrid system, PV hybrid power system. Basically, the bidirectional DC-DC converters are classified into two, according to the galvanic isolation between the battery and the grid [38]. These are:

- Non-isolated bidirectional DC-DC converter
- Isolated bidirectional DC-DC converter

3.2.1 Non-isolated bidirectional DC-DC converter

Non-isolated bidirectional DC-DC converters are employed when size and weight are to be considered, such as in aircraft power systems. This converter is simple and has fewer components than isolated bidirectional DC-DC converters [38]. Also, due to better efficiency and lower cost, the non-isolated converter is preferred than the isolated converter [33]. There are several non-isolated bidirectional DC-DC converters according to findings in different researches work. However, the famous and widely employed converter is half-bridge, and it operates in boost mode in one direction and buck mode in the other direction [39]. The transformerless non-isolated converter topology is more widely used than the isolated converter [37].

In the research papers [40] [41], cascade buck-boost DC-DC converter topology is proposed for bidirectional energy transfer. It operates as a buck converter while charging the battery, and as a boost converter when the power is delivering back to the grid to provide the inverter at a higher voltage. The input and output voltage levels differ from vehicle to vehicle. The buck-boost converter is used to achieve each vehicle requirement. The intermediate capacitor stores energy at a higher voltage to overlap the DC bus voltage and the battery voltage, as shown in Figure 3.7. Besides, this intermediate capacitor voltage can be altered to enhance the transient performance of the converter. The two stages separated by the capacitor give a better battery voltage capability, but higher power losses due to the increased number of switches. Generally, the cascade buck-boost converter has low efficiency, and performance falls when the voltage transfer degree rises.

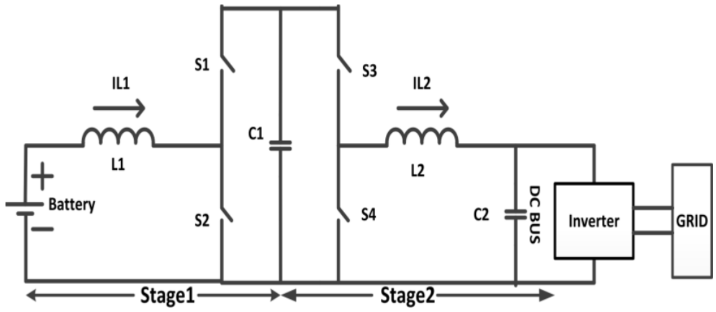

Figure 3.7: Cascade bidirectional DC-DC converter topology[40].

The half-bridge bidirectional DC-DC converter shown in Figure 3.9 is proposed in [42]. This topology needs two switches that can operate bidirectionally such as MOSFETs and IGBTs, and one inductor in the battery side to store energy during the charging and discharging of the battery. The bidirectional half-bridge DC-DC converter is derived from the basic buck and boost converters. The only buck and boost converters are not capable of power transfer bidirectionally due to the property of diode in the circuit, see Figure 3.8. The diode conducts only in one direction when it is forward biased.

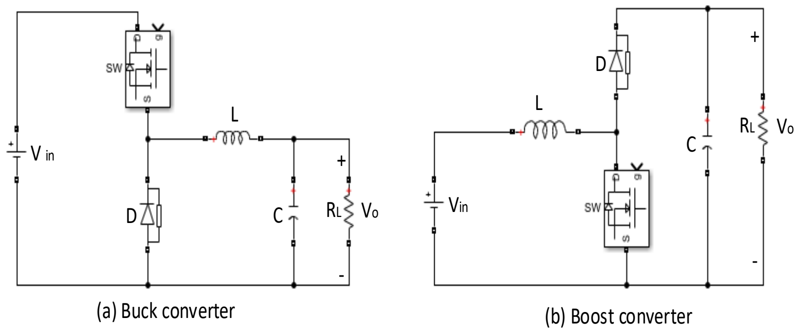

Figure 3.8: Unidirectional buck and boost converters.

To operate the buck-boost converter bidirectionally, replace the diode with controllable switch conducting in both directions like MOSFET or IGBT with an anti-parallel diode across them to allow two-way power flow. Figure 3.9 operates as a buck mode when power transfers from High voltage (HV) to low voltage (LV), and as boost mode during the reverse power transfer. On page 42, in the modeling of non-isolated bidirectional EV charger, this bidirectional buck-boost DC-DC converter is used to regulate the voltage level in the DC side. The reduced number of components, low cost, lightweight, and high efficiency make superior this topology [38].

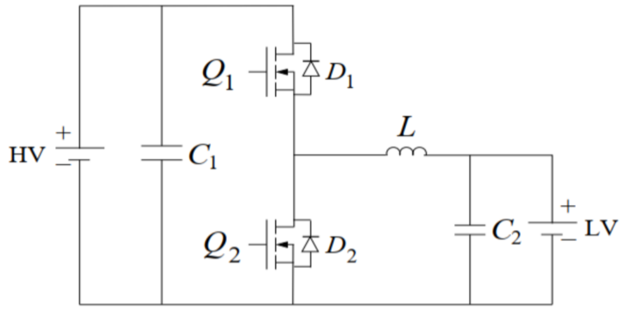

Figure 3.9: Buck-boost bidirectional DC-DC converter [42].

Another a three-level bidirectional DC-DC converter is proposed for a DC fast EV charging station in the research articles [39] [43]. The three-level topology is used in high voltage and high power rating applications, and it is known by less voltage stress across the switches. Also, it requires smaller passive components of inductors and capacitors. As shown in Figure 3.10, the three connection points p, n, z are connected to the DC-bus charging station, and the other end of the converter is connected to the battery. The modulation process generates the switching pulse, and by implementing a new modulation technique, the switching frequency can be reduced. Due to the reduced switching frequency, the losses across the switches can be decreased in this topology. The operation mode of the three-level bidirectional DC-DC converter is similar to the half-bridge converter, operates as boost mode during battery discharging and buck mode when the battery is charging.

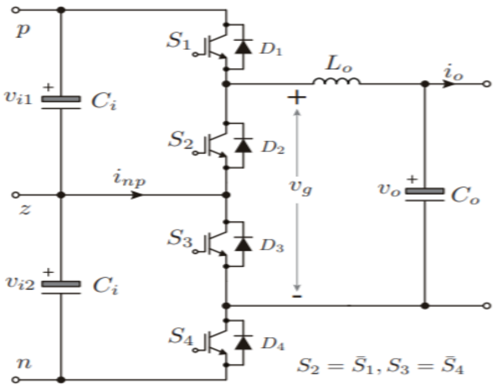

Figure 3.10: Bidirectional three-level DC-DC converter [43].

3.2.2 Isolated Bidirectional DC-DC converter

An isolated DC-DC converter is employed when it requires output and input to be separated to provide safety. In several applications, galvanic separation using the isolated converter is essential. The non-isolated topologies are convenient to use when the factor between input and output is small. However, applications with output voltage differ from the input voltage by a significant factor convenient to use an isolated converter. Hence, a high-frequency transformer must be added between the input and output stages for galvanic isolation, and a converter with high-frequency switching with bidirectional operation also requires. Half-bridge, full-bridge, and push-pull or center-tapped converters are widely used topologies. The transformer provides the galvanic separation and voltage matching between the mains and energy storage batteries in the bidirectional DC-DC converter. Besides, it gives multi-output connections and reduction of stress during switching operations [44]. The voltage level is adjusted by modifying the turns ratio of the transformer [38]. The transformer raises the size, losses, noise, and price of the converter. Even if the bidirectional isolated DC-DC converter is more expensive due to the increased devices, but it provides higher power density and fast control [30]. Some popular bidirectional DC-DC converters are reviewed below.

A bidirectional isolated dual-active-bridge (full-bridge) DC-DC converter is presented in [41] [45], as shown in Figure 3.11. C_1 in Figure 3.11 is connected to DC bus and the other end is coupled to the storage battery. Its galvanic separation is by a high-frequency transformer, which is smaller in size than the conventional transformer. The function of the bidirectional AC-DC bridge on both sides is to provide AC power to the high-frequency transformer and supplies DC to both ends of the converter. The DC voltage in C_1 is converted to AC to transfer the other side of the transformer in AC form and then converted to DC to store in the battery. Similarly, during power transfer from the battery, the battery DC voltage converted to AC then transferred to the other side of the transformer again convert to DC. The amount of power and its direction is controlled by the phase shift angle to achieve zero-voltage switching. The switching control can be done in several ways, and two of them are the following. *Either one bridge is phase shift controlled, and the other is uncontrolled (only anti-parallel diodes conduct), or both bridges output a square voltage wave, and the phase between two voltages square waveform can be controlled.* The latter one is the most popular and less complex, which is called a single phase-shift method. The polarity of the phase shift angle controls direction power flow, and the magnitude of the phase shift angle controls the amount of power transfer. Managing the amount and direction of power transfer using only one variable makes simple the single-phase shift technique [46]. This on-board converter shown Figure 3.11 is characterized by high power density, low harmonic distortion, unity power factor, excellent reliability. Besides, other advantages of the dual active bridge converter are soft-switching property, the evenly distributed current in the switches, and the few numbers of passive devices [47]. The dual-active-bridge topology operates efficiently if the ratio of the DC-voltage in the high voltage side and low voltage side is equal or close to the transformer turns ratio [48] [49]. In this topology, the capacitor in the storage sides of the DC-DC converter is tiny, and this makes it less costly, unlike the non-isolated Cascade DC-DC converter topology in Figure 3.7 used expensive, bulky capacitor [41]. The drawbacks of this converter are the narrow voltage range for best operation, and difficult to achieve high efficiency during light load due to high ratio reactive power to active power [45].

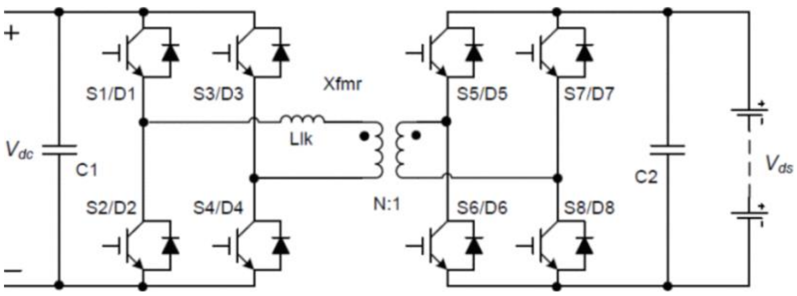

Figure 3.11: Bidirectional full-bridge DC-DC converter based on two voltage-fed [45].

The full-bridge bidirectional DC-DC converter shown in Figure 3.11 is made up of two voltage-fed full bridge S_1-S_4 and S_5-S_8. The power transfer P_s by this converter is presented below [48] [49].

$$P_s = \frac{V_1.N.V_2}{2.\pi.f_s.L_{lk}}.\varphi.(1-\frac{|\varphi|}{\pi}) \tag{3.12}$$

Where:

P_s real power transfer in the converter [W]

V_1 LV side amplitude voltage (the battery side) [V]

V_2 HV side amplitude voltage (the DC source) [V]

f_s frequency of the transformer [Hz]

φ the phase shift angle between the square wave in both terminals of the transformer [radian]

L_{lk} transformer linkage inductance [H]

N transformer turns ratio

$$d = \frac{V_2}{N.V_1} \tag{3.13}$$

So the per unit power (P_{pu}) is,

$$P_{pu} = \frac{1}{d}\varphi.(1-\frac{|\varphi|}{\pi}) \tag{3.14}$$

The calculation for the theoretical phase-shift angle φ is presented below, and the measured values of V_d, P_s and V_s are required to calculate the phase shift angle [48] [49].

During battery charging,

$$\varphi = \frac{\pi}{2} - \sqrt{\frac{\pi^2}{4} - \frac{w\pi LP_s}{V_1.N.V_2}} \tag{3.15}$$

During discharging,

$$\varphi = -\frac{\pi}{2} + \sqrt{\frac{\pi^2}{4} + \frac{w\pi LP_s}{V_1.N.V_2}} \tag{3.16}$$

The half-bridge isolated bidirectional DC-DC converter is made up of two half-bridge converters in the high voltage and low voltage sides of the high-frequency transformer, inductor L_{dc} on the low voltage side, and the small capacitors provide soft switching, as shown in Figure 3.12. When the power transfer is from low voltage side (LV) to high voltage side (HV), the converter operates in boost mode, and it functions as a buck converter in the reverse power transfer. During the boost mode, the converter in the LV works as a rectifier. Conversely, the converter in the HV operates as an inverter. During buck mode, the operation of the converters on both sides is the opposite to boost mode. The high-frequency transformer in this topology leads to a significant reduction in its size and the filter circuit. Switching for the converter can be used IGBTs or MOSFETs. The half-bridge arrangement converter has fewer devices compared to full-bridge and push-pull converter. Besides, the converter has a lower stress [50].

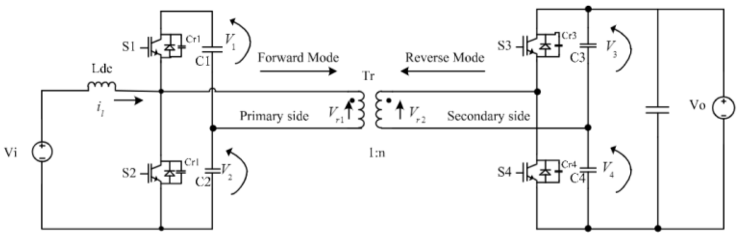

Figure 3.12: Half-bridge bidirectional DC-DC converter [50].

Isolated bidirectional DC-DC converter with a high-frequency transformer connected with full-bridge and center tapped push-pull circuit is proposed for vehicle electric power condition, as shown in Figure 3.13. The full-bridge circuit is high voltage side, and the center-tapped push-pull circuit is connected to the low voltage side. The operation mode of the converter in each side reverses when power flow direction changes. During the discharging mode, the center-tapped push-pull side works as a high-frequency inverter, whereas the full-bridge circuit acts as a high-frequency inverter during charging mode. PWM used to control the converter switching, and the voltage or current level is regulated by the duty cycle in the full-bridge circuit. In the full-bridge circuit, switches S1 and S4 are simultaneously on, and when these switches are off, switches S2 and S3 are on together to make a full loop. In the discharging mode, the low voltage side switches (S5 and S6) work with the overlapping interval [51].

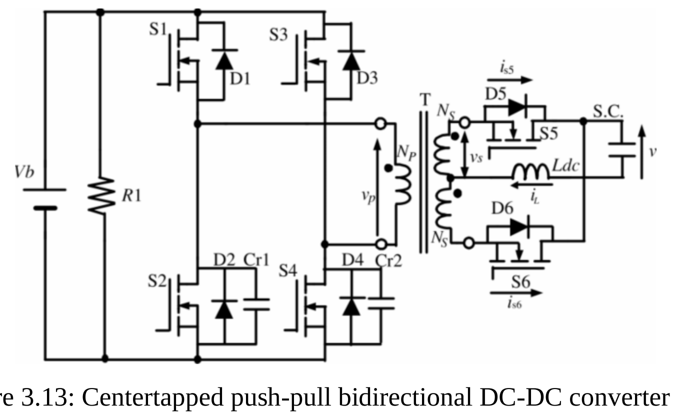

Figure 3.13: Centertapped push-pull bidirectional DC-DC converter [51].

3.3 Discussion

The purpose of the survey and study of different converter technology is to find an effective and appropriate converter for bidirectional power transfer between the grid and EV battery.

The focus of this study in this section is the bidirectional AC-DC and DC-DC converter. The DC-DC converter is further classified as an isolated or non-isolated converter. Comparing the advantages and disadvantages of the different converters help to arrive at an acceptable decision for modeling of the bidirectional EV charging station.

From all the bidirectional AC-DC converters reviewed, the three-phase two-level converter looks outstanding in implementing for modeling of two-way EV charger due to high power capacity despite its complexity compared to a single-phase converter. However, switching control is less complicated, and lower switching losses due to fewer devices compared to the three-level three-phase converter. A higher power factor describes the two-level three-phase AC-DC converter, reduced total harmonic distortion, ripple-free regulated DC bus voltage, which is insensitive to load, and supply variation are also the plus side of the converter.

The AC-DC converter can be directly connected to the EV battery without the DC-DC converter, which is to design a bidirectional EV charger with only one stage AC-DC converter that can reduce the price significantly. However, there will be no possibility of further voltage level regulating during charging and discharging. The DC-DC converter permits to step down the voltage during charging and to boost the voltage when power is exporting to the grid, but with a drawback of extra costs. Therefore, the investigation of the DC-DC converter is essential.

The galvanic isolated and non-isolated DC-DC converters for bidirectional power transfer are presented, and there are several topologies in both types. Both converters have advantages and disadvantages. The downside of an isolated converter is the current in the low voltage side of the transformer is high, and this can cause to decrease in the efficiency of the topology. Besides the cost and complexity increase in the isolated converter. Therefore, the transformerless non-isolated converter topology more widely used. Half-bridge DC-DC converter is the most common in the non-isolated converters due to high efficiency and compact size. The cascade non-isolated bidirectional DC-DC converter topology can also be used for additional voltage regulation. However, the performance of the converter decreases when the voltage level increases and the increased number of switches boost losses. The three-level non-isolated bidirectional DC-DC converter has the capability of high voltage and high power transfer, and it has low voltage stress. However, the increased number of switches and passive components raise the cost of the converter.

4 Standards for Charging and Discharging Electric Vehicle

In the past years, the electric vehicle battery charger has been an attractive research topic, mainly bidirectional chargers. This section will present the available unidirectional and bidirectional chargers for EVs.

Plug-in electric vehicle (PEV) requires a power electronic connection between the power grid and the battery pack for charging. The main converter is located inside the car connected with EVSE if it is an on-board charging system and outside the vehicle for an off-board charger. EVSE is equipment or a combination of several pieces of equipment that connects the grid or local supply to the EV for charging. In AC charging or on-board charging, only the cable assembly considered as EVSE, and in a DC fast charging, EVSE is the combination of the cable assembly and charging station, which is the converter [52]. Figure 4.1 shows some types of on-board and off-board connectors with different charging speeds.

Figure 4.1: Some types of on-board and off-board connectors [53].

In essence, there are two types of EV charging. The first one is the AC charging station, which is called an on-board charger (OBC) and further divide as level 1 and level 2. In this case, the EV is directly connected to the grid with electric vehicle supply equipment (EVSE), and the power conversion from AC to DC to provide DC power to the battery pack is done inside the vehicle. If the car is equipped with bidirectional power transfer, the DC to AC conversion is done inside the vehicle. The next is the DC fast charging, which the EV battery pack is directly connected to the standalone converter outside of the vehicle and is also called an off-board charger. Indeed, this converter is larger than the converter inside the car itself. The battery pack is directly connected to the converter, so this implies that it is easier to extract energy from the battery pack if the converter is bidirectional. Furthermore, the EV charging station can be classified as a unidirectional and bidirectional charger. The bidirectional charger supports injecting power from the battery pack back to the electric utility besides the charging. A two-way off-board charging station is consisting of a DC-DC bidirectional power converter, and an AC-DC bidirectional power converter [36].

Depending on voltage and frequency, the arrangement of the charging station, electrical grid connections, and standards differ from country to country. EV's battery life and charging time depends on the property of the charger. A good charger is characterized by its high efficiency, reliability, high power density, low cost, low volume, and low weight. Charging level is the main criterion that affects the charging time, price of equipment, and effect in the grid. The characteristics of the EV battery charger mentioned above corresponds to an ideal charger. In fact, some properties are missing in the on-board charger, and others are not present in the off-board charger. According to market request and in designing the converter topology, some characteristics are included, and others are excluded. The level of charging, type of switching method, and control algorism depends on the physical battery charger [30].

In the EV charging system, a new concept of classification is emerging according to energy transfer, conductive and inductive charging system. The conductive system is the conventional charging system that has a physical connection EV and charging inlet point. On-board (level 1 and level 2) and off-board (level 3) both are under the conductive charging system, and it is efficient and simple. The other new unmatured concept is the inductive charging system known as a wireless charging system, no need direct contact supply system with EV. According to March 26, 2019, the city of Oslo is working together with Forum and American company Momentum Dynamics to develop the world's first fast wireless charging stations for taxis in Oslo. Oslo is already a city with plenty of electric vehicles. However, conventional chargers are not suitable for charging taxis; that's why it is time to find fast, easy, and automatic charging. They are working to install a 75 kW wireless fast-charging station in the ground, which is in the taxis' parking places. The plan in Oslo is to change all taxis to zero-emission taxis by 2023. Power transfer to the EV is by an electromagnetic field, and the advantage of wireless charging is electrical safety at different weather, user convenience, and durability. The negative sides are complex infrastructure, lower efficiency, high power loss, high cost, low power density, size increased. And another vital question is the impact of energy radiated as losses from the wireless charging on the health of the drive as they stay inside the car during charging, and it is every day [30] [54].

4.1 Unidirectional Charging and Charging Levels

When EV is connected to a supply system, it is considered as a load, and it serves as a distributed energy storage system when power is flowing back to the grid from the EV. Hence, in the unidirectional charge, the EV is only able to charge. The configuration for this charger needs the AC-DC converter with diodes, filter devices, and it requires a DC-DC converter if it needs further voltage regulation like the charger level 3. When injecting power to the grid is not required, the unidirectional charger is preferred because of easiness to control the converter, and reduced cost [30].

All charging stations are not at the same charging levels, and the charging time depends on the amount charging power or the voltage and the current level. There are three types of chargers, and these are level 1, level 2, level 3. Level 3 is a DC fast charging, and as the name indicates, it allows the quickest charging.

4.1.1 Level 1 Charging

Level 1 charging is on-board charging, which connects to a standard household electrical outlet. In Europe, the voltage is single-phase 230 V and 120 V in the US, though the current is the same in both 15 A. As power is the product of voltage and current, the charging time is faster in Europe. Level 1 offers the slowest charging speed than the other two charging levels, and the plus side of this charger is cheap, and there is no installation cost. The price and less installation make the level 1 charging popular for residential usage. However, level 1 is not practical for PEVs because it will take one day from 0 to almost fully charge [55]. Due to low charging power, level 1 charging does not cause a significant influence on the distribution network [56].

4.1.2 Level 2 Charging

Level 2 charging is connected to three-phase 400 V, 32 A constitute to 22 kW. Level 2 charger provides faster-charging speed compared to level 1 because of its higher power capability. Level 2 charging is a typical charging station which the primary and most common for public and home use. Although this charging level takes shorter than level 1, requirements for installations boost the price. The price of installing level 2 at home may reach about $1000-2000. A portable converter (Quick 220®) is available at a fraction of the cost of the traditional method to avoid installing the expensive charging station. But Quick 220® is not under the standard charging system. Only plug-in EV may require level 2 charging to charge the battery fully overnight. However, PHEV can also be fully charged by level 1 overnight [55]. Level 2 charging has a higher power capacity than level 1, which can impose a considerable load increase in the distribution system, even a small number of EVs. Hence, proper management of charging EVs is essential to avoid phase inbalance, overloading of feeders, reduced power quality, and fuse burning [56].

4.1.3 DC Fast/Level 3 Charging

Level 3 charger is off-board DC fast charging connects directly to the EV battery and provides the highest power because conversion is outside the vehicle. DC fast charger is usually owned by commercials only, and it is rarely or may not found in the workplace and at home because of different reasons. First, the amount of power required is high, and there is a probability that the consumption power to exceed the rating of existing appliances. Also, the distribution network in the area is not designed to handle a high amount of power, so the elements in the distribution system should be either replaced, or they will be destroyed due to overloading. Additionally, a three-phase connection may need due to the increased amount of power, and the price is also high [57]. In DC fast-charging station, it depends on what type of EV battery is connecting instead of the kind of connection to the supply [58]. Not all EVs can charge with DC fast charging, so checking the manufacture's manual before connecting to the DC source is very important [55].

In CHAdeMO fast charging, the CAN communication is used to control the amount of current needed for each vehicle based on real-time. The system provides a wide range of charging current. The communication system between the supply and EV plays an important role, so if a communication line fails, charging stops [59].

According to the study presented in [60], there are three DC fast charging available with the specification of IEC 61851 standard or GB/T 18487 standards.

i. CCS (all US and german cars)
ii. CHAdeMO (Nisan, Mitsubishi, and Kia)
iii. GB/T (China)

The output power level of the DC fast charging has been updated from one level to another level with time. Consequently, it has been made some confusion, so to avoid the uncertainty, Table 4-1 shows the information given by CCS and CHAdeMO standards.

Table 4-1: Output power level classification for DC chargers according to CHAdeMO and CCS standards [60]

	Version	Output Power [kW]
CHAdeMO	1.0	$62.5(500\ \mathrm{V} \times 125\ \mathrm{A})$
	1.2	$200(500\ \mathrm{V} \times 400\ \mathrm{A})$
	2.0	$400(1\mathrm{kV} \times 400\ \mathrm{A})$
CCS	DC5	$5(500\ \mathrm{V} \times 10\ \mathrm{A})$
	DC10	$10(500\ \mathrm{V} \times 20\ \mathrm{A})$
	DC20	$20(500\ \mathrm{V} \times 40\ \mathrm{A})$
	FC50	$50(500\ \mathrm{V} \times 100\ \mathrm{A})$
	HPC150	$150(500\ \mathrm{V} \times 300\ \mathrm{A}, 920\ \mathrm{V} \times 163\ \mathrm{A})$
	HPC250	$250(500\ \mathrm{V} \times 500\ \mathrm{A}, 920\ \mathrm{V} \times 271\ \mathrm{A})$
	HPC350	$350(500\ \mathrm{V} \times 500\ \mathrm{A}, 920\ \mathrm{V} \times 380\ \mathrm{A})$

4.2 Charging at Public Stations

Driving EV needs more planning than traditional cars, which use gas. There are several things to consider, such as state of charge of the battery, the length of the journey, charging station in the way, the time takes the car to charge, and soon. In a public charging station, the charging rate appears once the battery reaches 50%, and the charging slows significantly when it reaches 80%. It may disconnect in some chargers to open up for others [55].

Finding a public charging station in large cities have no trouble, but areas with less population are far behind in public charging infrastructure. However, there are excellent apps available online to find the nearest public charging station. These are the top worldwide apps used to find the nearest public charging station [55]:

- Plugshre
- Green Charge
- Open Charge Map
- EV Trip Planner
- Charge Hub
- ChargePoint
- Blink
- CarStations

4.3 EV Charging Connectors Standards

There are three primary EV charging standards. These are; Asian vehicle producers use CHAdeMO, combined charging system (CCS) is more widespread in Europe and North America, and Guobiao recommended-standard (GB/T) is China national standard. These three charging standards are issued as international standards by the International Electrotechnical Commission (IEC 6185-23 and -24). The type of communication or security procedures and the connector type are the main differences among the charging standards [52]. The communication in CHAdeMO is more complicated than the others. The communication EV battery and the power source play a significant part in the lifetime of the battery and charging interfaces and also safety for the user, especially in an on-board charger. The EV detects fully and proper connection both sides to the vehicle and the supply. The latch (switch) is used to stop charging. When the latch is initiated to hold charging, the EV should detect and stop charging to avoid arcing during unplugging. As the electricity rates vary within the day, the smart charger allows EV to connect and disconnect based on the electricity price to charge at the lowest price [58].

4.4 Bidirectional Charging Standards

The concept of bidirectional EV charger has been in a long time, and the oldest academic study documented was by the University of Delaware in the USA in 1997. The name V2G was not used at that time, but the idea was the same by charging EV at low electric demand and support the grid at peak hours. After that, there have been several types of research on this topic, but the first research seemed to implement in reality was from Nissan Leaf in 2010. In 2011, the Tohoku earthquake caused significant destruction in the Japanese electrical generation system. The Fukushima Daiichi Nuclear power plant disaster encouraged the Japanese energy companies to explore an alternative that people can get access to electricity. By that time, EVs were already widely distributed in Japan. Therefore, stationary battery or EV with a bidirectional charger came as a solution to provide backup power to homes during blackouts or emergencies. That incidence accelerated to mature the V2G technology earlier than another part of the world. The first commercial V2G technology implemented in the world is in Danmark in 2016 by Nissan Leaf by collaboration with Enel and Nuveen. Enel is an Italian multinational company which works in electrical generation and distribution, and also in natural gas distribution [53] [61].

With the increase of EV in the roads, bidirectional chargers are becoming more popular to inject power back to the grid for balancing between consumption and generation of electrical energy. Instead of changing the power system generation, EVs can serve as a short-term energy reserve. A system with fast coordination between the EVs and the utility, the EVs can also be used for frequency balance if there is excess energy in the power system. As the name indicates, the bidirectional charger enables the vehicle to import electrical power from the grid and export electrical power to the grid. The name V2G is used to indicate both direction power transfer. It is also possible to charge with the traditional one-way charger and connect the bidirectional charger when it is required to provide to the grid. The concept of V2G includes vehicle-to-home (V2H when EV connected to a residential), and vehicle-to-building (V2B when EV is at a commercial building) [13]. Homeowners can benefit from this advantage in case of an emergency if a sudden blackout happens because of a natural disaster like storms. The idea of bidirectional charging is similar to smart charging. Smart charging allows charging the vehicle based on the state of the power system. When the car is charging and if the demand raised, the car stops charging to support the grid [62]. However, the V2G technology can offer the customers revenue from providing power to the grid. A single private vehicle seems no impact or can not make revenue, but a group of cars or fleet vehicles can make a change. In the UK, companies are developing V2G technology to do business by exporting power to the grid. However, the charger should be compatible with CHAdeMO and CCS, and it needs to get approval from the carmaker (safety for the vehicle battery) as well as it must comply with the distribution part of the grid [53].

The bidirectional charger for EV is not only used to connect the car with the grid, vehicle-to-vehicle (V2V), and vehicle-to-home (V2H) are also essential applications of EVs two-way power transfer. The V2H concept is the stored energy in EV battery is used as back up to power a home. Also, the V2V idea is to implement an energy exchange between two EVs by charging one and discharging the other [30].

Currently, the only charging standard for bidirectional power transfer is possible with CHAdeMO DC fast charger, which developed in Japan. Most of the time, DC fast charging is available in public and commercial areas [63]. Some times the V2G is replaced by V2X, which means vehicle-to-everything. The detail for the CHAdeMO protocol is available only to members. The system is already implemented in Japan, the US, and Europe. It is anticipated that the V2G may give extra revenues cost saving of 2 billion US dollar for global energy providers and 15% saving on energy consumption at home for customers [64].

At this time of writing the thesis report, no standard CCS connector in use for the V2G application. The CharIN initiative is working on the development of network integration and bidirectional charging (V2G) based on the ISO/IEC 15118 in the CCS standards. The Charging Interface Initiative EV (CharIN) is an association that has more than 150 international members from Europe, North America, as well as from Asia, and its head office is in Berlin. The association aims to make the CCS charging standard worldwide for charging all types of electric-powered vehicles [65] [66]. Japan depends on CHAdeMO already developed its bidirectional charger, and China has its own standard (GB/T). The CharIN has been working on distributing the combined charging system (CCS) globally. Now, the CHarIN is working on developing the bidirectional charging integration. The target of the association is to provide the bidirectional charger by 2025 classified into two types [65] [67]:

- Level 3: V2H bidirectional charging
- Level 4: V2G Agriggated (bidirectional) charging

Very recently, the CHAdeMO Association, in collaboration with China, released a new electric vehicle fast-charging standard version 3.0. The new charger version has the capability of taking power from the EV battery and export it back to the grid, which is bidirectional. The CCS standard is still lagging in the bidirectional connector. This connector can handle more than 500 kW and a maximum current of 600 A [68] [69].

Moreover, ISO 15118-20 is an international standard that responsible for the vehicle-to-grid communication interface [70]. The EV should send a ServiceDiscovery to the charging station to check the available type of charging. The possible services in the charging station are AC, DC, automatic connection device (ACD), and wireless power transfer (WPT). Currently, bidirectional power transfer (BPT) is possible with AC and DC connection. If the option BPT is selected, it will enable the vehicle to charge and discharge during the connection time. The reverse power flow is suitable in an office or at home where the connection time of the car with the charging station is long enough. According to the founds, the bidirectional power flow is possible with the Japanese CHAdeMO standards (Nissan, Kia, and Mitsubishi) [71].

There several small companies producing EV connectors or chargers but not authorized as a standard connector. In Finland, a bidirectional EV charging station is installed in cooperation with Virta (EV charging company), Helen (electric energy production company in Finland), and Nissan. The charging station designed by Virta, which is compatible with the Nissan connector, but the connector is not registered as a standard charger for the V2G system. This charging station is a practical experiment to expand in the future. The charging station is also connected to a solar power plant. When solar power is available, the vehicles charge from it and provide support to the grid during peak hours or when emergency help required. The willingness of EV owners to participate in balancing the grid is also essential in expanding V2G technology [72].

Another small company known as Wallbox (Spanish charging technology maker) made a bidirectional charger with the CHAdeMO connector, where called Quasar. It is compact and capable of 7.4 kW (240 V x 32 A) both directions. The interface in the vehicle is with the DC port as the conversion is in the charger. The available product works only Nissan Leaf and Mitsubishi (CHAdeMO), but they are speaking with other EV companies to make it possible for other more EVs. Charger Quasar is also not recognized as a standard connector. Depending on the size of the battery, Quasar is supposed to power regular householding with the 7.4 kW [73]. Quasar is also a solution for a place that suffers from natural disasters frequently like Japan, with the principle of V2H/V2B.

Figure 4.2: Wallbox bidirectional charger[74].

4.5 Discussion

The EVs can be charged either with unidirectional or bidirectional charger. However, pushing power back to the grid is possible only by a charger with two-way power transfer capability. In some cases, businesses or building owners may want to use the bidirectional EV charger to connect a backup power from the vehicle in addition to supplying power to the grid. Providing power a building from a car is similar to private roof solar power, but the photovoltaic does not have the bidirectional power transfer capability. As mentioned above, providing power to home or building from a vehicle is known as V2H/V2B. In the V2B or V2H, the electric utility is not participating directly when power transfer from the vehicle to the building. However, the utility benefits when customers are disconnecting from the grid to reduce power at peak-hours, and they provide electricity their home from the energy stored in the EV battery during low demand. The system is less complicated than the V2G as no need for coordination and communication the vehicle with the grid. Still, it has less attractiveness due to the participants' use only in on-peak times and the regulation for anti-islanding. Generally, the popularity of bidirectional EV chargers is increasing as some companies such as Virta and Wallbox are providing their products. Virta is implemented for public bidirectional EV charging stations started in Finland for the first time and is distributing in other parts of the world. And Wallbox is a bidirectional charger used to power home from energy stored in an EV battery as a back source. However, these two bidirectional chargers are not recognized as standard connectors.

5 Bidirectional Electric Vehicle Charger Model without Galvanic Separation

An essential property of a bidirectional EV charger is the ability to inject power from the battery and push back to the grid in addition to the conventional charging. Section 3 presents several converter topologies that proposed for bidirectional EV charger either two-stage or single-stage from different works of literature. In this section, by evaluating all the reviewed converters, EV charger with the two-stage conversion with the possibility of two-way power transfer is modeled and simulated. Figure 5.1 shows the simplified topology for the V2G EV charger developed in MATLAB/Simulink environment. The charger with two-stage of conversion is made of two converters. The two-level three-phase bidirectional AC-DC converter is using six switches connected to the three-phase grid, and the half-bridge buck/boost bidirectional DC-DC converter uses two switches, which joins the DC-link and battery pack. The two-stage topology has an advantage of better DC voltage regulation despite the drawback of increased size and cost [75].

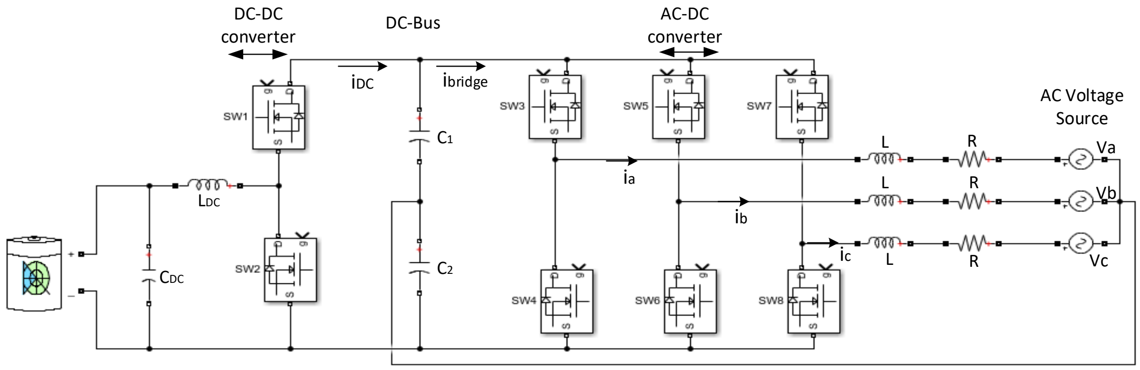

Figure 5.1: A simplified two-stage bidirectional EV charger without galvanic isolation.

Importantly, the V2G technology is expected to play a significant role in enhancing the reliability and efficiency of the renewable energy dominated grid. EV with a unidirectional charger can also support the power system balance, but not as EV with a bidirectional charger. The primary way to balance the load in the system with a conventional unidirectional charger can be accomplished by increasing and decreasing the EV charging according to the status of the electric utility, and this is called peak shaving or load shifting. A wind power plant can be taken as an example, at a particular time like at night, and let's say the wind turbine has surplus power. If the produced excess energy is not used or sold to a neighboring country, the only option is to shut down the turbines to maintain nominal frequency and avoid instability in the network. However, if there are several vehicles with a bidirectional connection, the wind turbine can be saved from the shutdown by charging the cars at this particular time and push back to the grid during peak-hours [28]. From this, the significance and benefits of the bidirectional charger over the traditional charger motivate to investigate it. This section presents the step by step modeling of the bidirectional EV charger in MATLAB/Simulink, the simulation result, and its discussion.

5.1 Half-Bridge Single-Phase Bidirectional AC-DC converter

In this thesis, the front end of the bidirectional EV charger is modeled with a three-phase AC-DC converter. However, for simplicity and to study the behavior easier, a half-bridge single-phase AC-DC converter is analyzed and tested first. The converter needs two power electronic switches either IGBTs or MOSFETs with complementary switching mode, MOSFETs are used in this circuit used here. The MOSFET internal on resistance and internal resistance of the anti-parallel diode is set to default values, and this applies to all the simulations of the AC-DC converter. Sinusoidal PWM (SPWM) method is employed to generate the gate pulse of the switches, see Figure 5.2. The frequency of the sine wave is 50 Hz, which is the same as the AC voltage source to produce voltage and current from the converter at the same frequency with the fundamental AC source during the inverter mode. The switches are triggered alternately, which means when SW1 is on, SW2 is off, and vise versa. The DC voltage sources are both 500 V, and the AC voltage source is 480 V.

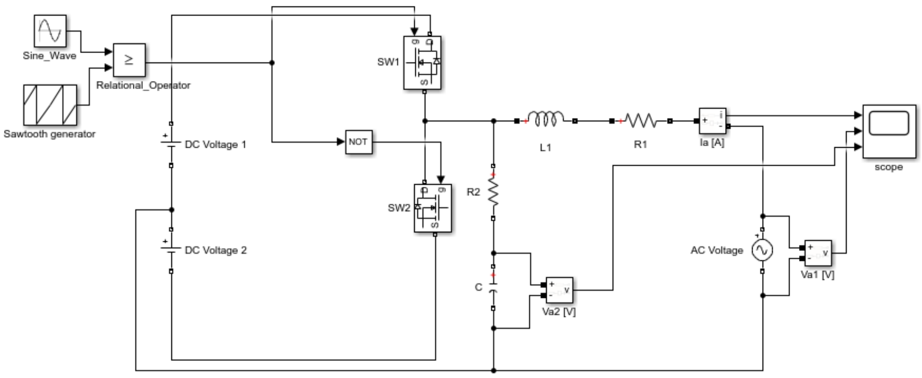

Figure 5.2: Half-bridge single-phase bidirectional AC-DC converter.

The parameters used in this simulation are listed in the table below.

Table 5-1: Parameters used for half-bridge of bidirectional AC-DC converter simulation.

Parameters	Values
AC voltage source	480 V
Inductor, L	5.5 mH
Resistor, R_1	1 mΩ
Resistor, R_2	100 Ω
Capacitor, C	1 μF
DC voltage sources	500 V

5.1.1.1 Simulation Result

The phase angle of the sine wave in the SPWM controls the mode of operation of the converter, which means it controls the direction of power flow. If the phase angle is zero, there is no power transfer between the AC and the DC side due to zero current flow, as shown in Figure 5.3. Besides, the amount of power transfer is also controlled by varying the phase angle.

During rectifier mode, the power transfer from the AC side to the DC side. For pure active power transferring, the phase angle of the sine wave is negative, and the AC voltage source and current are 180° out of phase. During the inverter mode, the half-bridge single-phase AC-DC converter operates as a voltage source inverter to convert the DC bus voltage to a single-phase AC voltage at the same amplitude and frequency of the AC source. To transfer power from the DC side to the AC side, the phase angle for the sine wave is positive, and the voltage and current are in phase. Figure 5.4 and Figure 5.5 shows the simulation result for both rectifier and inverter modes for the converter, respectively. In the rectifier mode, voltage and current are 180° out of phase. Under the inverter mode, the current and voltage are in phase, and the phase angle is set to -1° and 1° in the rectifier and inverter mode, respectively.

The sine wave in the SPWM controls the frequency, amplitude of the voltage generated by the inverter. The magnitude of the AC voltage source and the voltage converted by the inverter must be synchronized with the fundamental AC source. In order to get the voltages of the same in magnitude, the amplitude of the sine wave is set the ratio of AC voltage source (480) to half of the DC voltage source (500 V). The AC voltage source must always be lower than half of the DC voltage source to avoid overmodulation in the switching because of the amplitude of sawtooth extends from -1 to 1. In the half-bridge converter, the peak voltage produced by the inverter is half of the DC voltage source. As shown in Figure 5.2, two equal voltage sources are connected in series and divided by a neutral line from the AC source. As a result, the DC voltage source divides into two halves, and the voltage available in each half cycle is 500 V. The half-bridge converter is simple, but the drawback of the converter is the peak voltage of the inverter is half of the DC supply voltage.

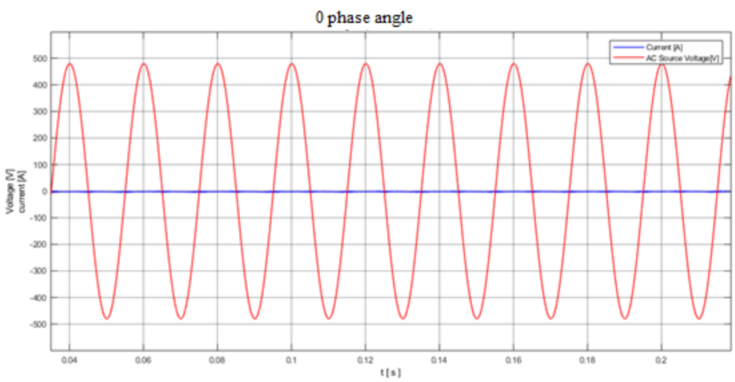

Figure 5.3: When the phase shift is 0° in a sine wave, no current flow.

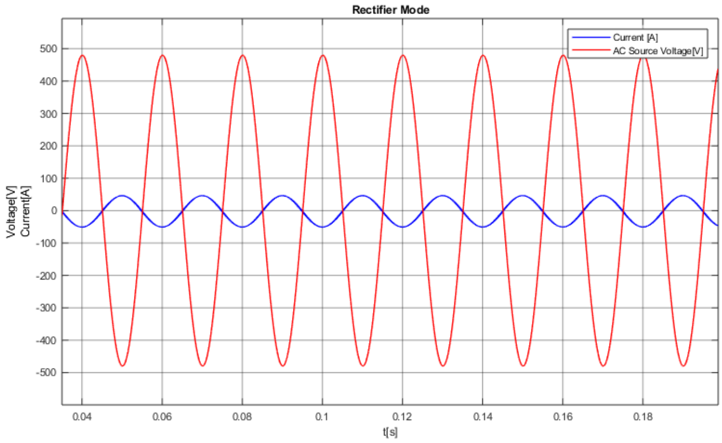

Figure 5.4: AC voltage and current under rectifier mode with a 1° phase angle.

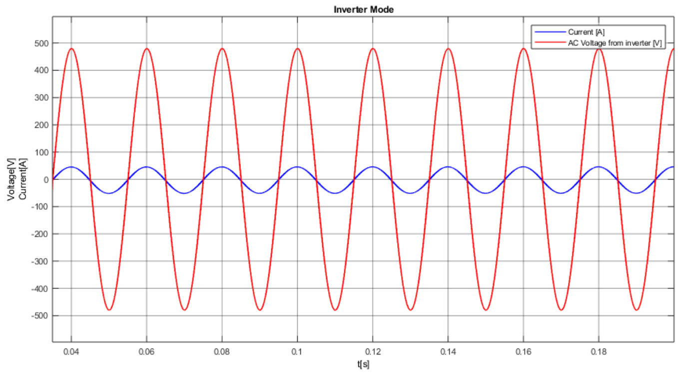

Figure 5.5: AC voltage and current under inverter mode with a 1° phase angle.

As the phase angle and current have proportional relation, Figure 5.6 displays the amplitude of current doubled as a result of increasing phase angle twice in PWM.

Figure 5.7 presents the simulation result for rectifier and inverter mode together. The voltages in both operations have the same amplitude, in phase, and completely overlapping. The current in rectifier and inverter mode has a 180° phase shift, but the same magnitude. This 180° phase shift of current in inverter and rectifier mode implies current direction reverses when the mode of operation of the converter changes. Therefore, it is clear from the figure that the power transfer reverses when the current flow reverses.

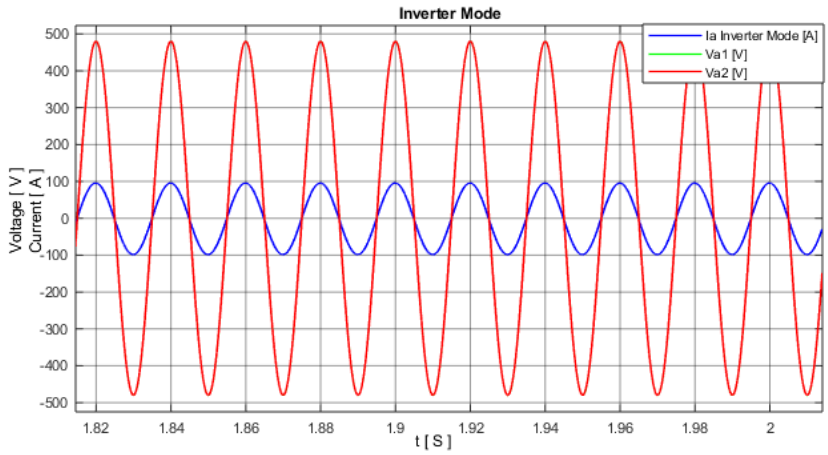

Figure 5.6: AC voltage and current under inverter mode with a 2° phase angle.

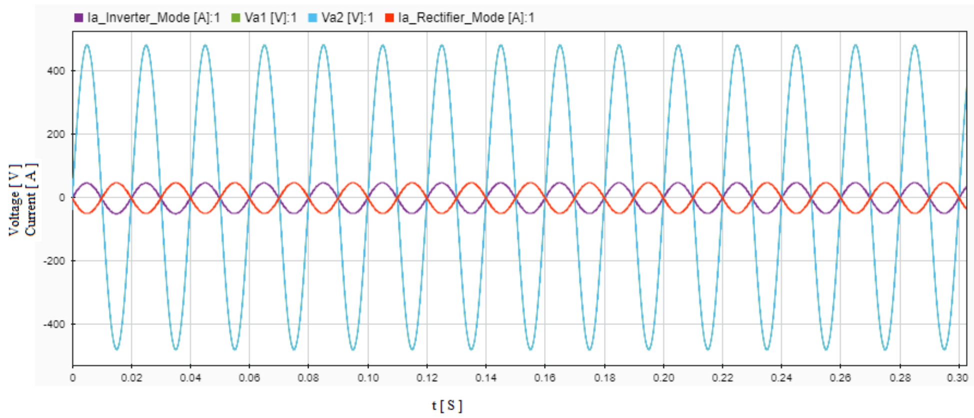

Figure 5.7: AC voltage and current for both rectifier and inverter mode.

5.2 Bidirectional DC-DC converter

A bidirectional DC-DC converter is applicable for efficient electrical power transfer and battery charging. The DC-DC converter part of the full two-stage bidirectional charging station is presented here in this subsection. As shown in

Figure 5.8, a non-isolated half-bridge buck-boost converter connected with the battery, and V_{DC} is connected with the DC side of the AC-DC converter in the complete model. As the name indicates, the converter operates in both buck and boost modes. The DC-DC converter works as a step-down converter during battery charging $(i_{DC} < 0)$ and a step-up converter if the battery is discharging $(i_{DC} > 0)$ to the grid. The importance of the DC-DC converter is to provide DC voltage regulation. Particularly in this work, to step down the charging voltage according to the battery requirement during charing and step up during discharging. Different vehicles may need a different voltage level, and charging voltage may require to change with the state of charge of the battery. So, the voltage level can be regulated easily by changing the switching duty cycle. Also, in the reverse power flow from EV battery to the grid, it needs to step up the discharging battery voltage to provide a regulated DC bus voltage by varying the switching duty cycle regardless of the state of charge of the battery.

The non-isolated bidirectional half-bridge converter operates in both buck and boost mode, which is developed by the combination of separate buck and boost converters from Figure 3.8. The MOSFET internal on resistance and internal resistance of the anti-parallel diode is set to the default values in the half-bridge DC-DC converter.

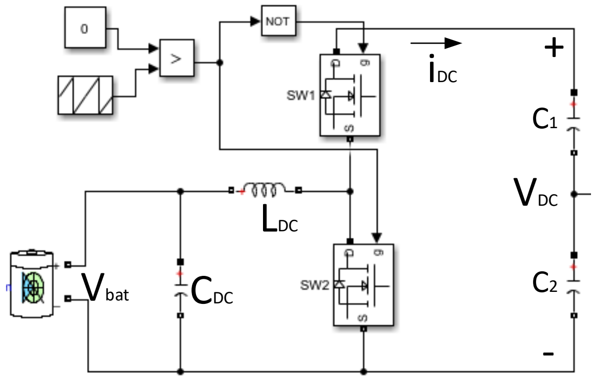

Figure 5.8: Bidirectional DC-DC converter.

The components used in the DC-DC converter model from the Simulink library are:

- Lithium-Ion battery with a nominal voltage of 500 V.
- Capacitor
- Inductor
- 2 MOSFET switches
- Sawtooth carrier signal extends from -1 to 1 and frequency of 25 kHz.
- A constant block for control signal.

The half-bridge bidirectional DC-DC converter is tested separately, but it is not presented here to avoid repetition. When it operates independently, the direction of power transfer is controlled by varying the switching duty cycle. When the duty cycle is 50%, no current flow, and if the duty cycle is less than 50%, the current flow from the LV to the HV side. Conversely, power transfer from the HV to the LV side if the duty cycle is set higher than 50%. However, according to the simulation test, when the DC-DC converter is combined with the AC-DC converter, the direction of power flow is managed only by the AC-DC converter. AS shown in

Figure 5.8, by connecting logical not block either of the switches, the converter operates appropriately, and the simulation results presented are in this principle.

5.2.1.1 Buck Converter Mode

The converter works as a buck mode while the EV battery is charging. The average output voltage is always lower or equal than the input voltage (DC-link voltage, V_{DC}). When the converter is operating as a buck mode, DC-link voltage is assumed as the input voltage to the converter and the battery terminal voltage as output. The output voltage level is controlled by varying the duty cycle of the switching, as shown in the Equation (5.1). As the switching duty cycle (D) is between 0 and 1, it is clear that the output of the step-down converter is always less or equal to the input voltage. The low-pass filter made up of capacitor and inductor in the battery side provides stable voltage to the battery. As shown in

Figure 5.8, the switching is PWM, in which the sawtooth modulating signal is compared with a constant control signal to produce the switching pulse to trigger the gate of the switches. The amplitude peak to peak of the sawtooth modulating signal extends from -1 to 1. For generating a switching pulse with a 50% duty cycle, the constant control signal must be 0. The DC-bus voltage output of the AC-DC converter is 1000 V. The simulation result in Figure 5.9 verifies Equation (5.1) the expected average output voltage 500 V. To avoid initial transient voltage, setting the steady-state voltage as an initial condition for the capacitor and steady-state current for the inductor is essential.

$$V_{bat} = DV_{DC} \tag{5.1}$$

Where:

D	the ratio of switching on time [t_{on}] to switching period ($\frac{t_{on}}{T_s}$) [T_s]
V_{bat}	the voltage in the battery terminal [V]
V_{DC}	the voltage in the DC-bus [V]
D	duty cycle
t_{on}	a time the switch is on [s]
T_s	switching period [s]

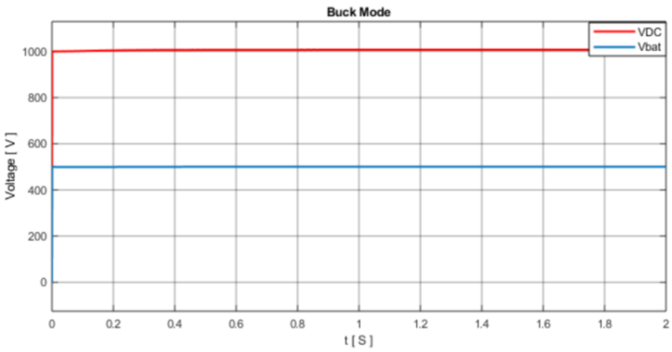

Figure 5.9: Input and Output voltages of the bidirectional DC-DC converter in buck mode.

5.2.1.2 Boost Converter Mode

The converter operates as a boost converter when the battery is discharging to provide support for the grid. The boost mode during battery discharging raises the battery voltage and provides a regulated voltage to the DC-bus no matter the state of charge of the battery. Generally, the importance of providing the voltage source inverter at higher voltage is to reduce the switching losses as the ohmic losses depend on current. So, to transfer the same power, and if the voltage increases, the current decreases, so the reduction in current lower the losses in the components. Therefore, the boost converter is vital in the implementation of the bidirectional EV charging station. When the converter operates in boost mode, similar to the buck mode, the switching duty cycle (D) controls the output voltage. However, in boost mode, the output voltage (V_{DC})

of a step-up converter is always higher or equal to the input voltage (V_{bat}) as the duty cycle is between 1 and 0, and it is also clear from Equation (5.2). In the discharging mode, the battery voltage 500 V is input to the DC-DC converter with a switching duty cycle of 50%. Figure 5.10 displays the simulation result for boost mode, which confirms the theory and Equation (5.2).

$$V_{bat} = \frac{1}{1-D} V_{DC} \tag{5.2}$$

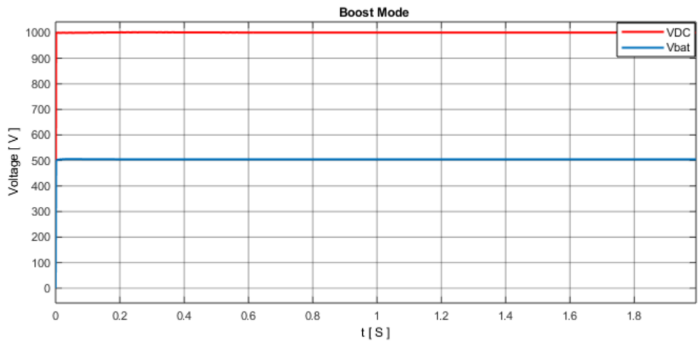

Figure 5.10: Input and Output voltages of the bidirectional DC-DC converter in Boost mode.

When power is transferring from the battery to the grid, and the AC-DC converter in Figure 5.1 operates as an inverter, the DC link voltage may be expressed as follows in Equation (5.3) [10]. At steady-state, the current in both sides of the DC-link (i_{DC} and i_{bridge}) are equal, and this implies DC-bus voltage is stable and constant. Where C_{bus} is the total capacitance in the DC-bus.

$$\frac{dv_{DC}}{dt} = \frac{1}{C_{bus}} (i_{DC} - i_{bridge}) \tag{5.3}$$

5.3 Combined Bidirectional AC-DC and DC-DC Converter

Almost all residential, industrial, and commercial require AC power supply, but electrical energy can not be stored in AC form to use by EV itself or to supply back to the grid when it is needed. Therefore, the bidirectional AC-DC converter requires to charge the EV battery from the AC mains. The bidirectional AC-DC converter operates in two modes, namely as front-end rectifier when power transfer is from the three-phase grid to the EV battery. And it works as a voltage source inverter while the EV battery is pushing back power to the three-phase mains.

The full EV charger simulation model without galvanic isolation is developed in MATLAB/Simulink, as shown in Figure 5.1, and Table 5-2 presents the parameters used to run the simulation. The semiconductor devices and the battery used in the model are from the toolbox called Simscape/Simscape power system. The model consists of two stages of converters, namely DC-DC and AC-DC. The DC-DC converter is connected to the EV battery to step down the voltage according to the battery requirement during charging. Also, to step up the battery voltage during discharging to the grid. Three-phase two-level AC-DC converter with bidirectional power transfer capability is connected to the grid, and it consists of six switches. All the switches used are power MOSFETs.

The operating principle for the DC-DC converter part is presented in a separate subsection in detail. It operates as boost mode during discharging, and buck mode during charging. The voltage level in both modes is controlled by the duty cycle of the switching.

In the bidirectional AC-DC converter part, the working principle is similar to the single-phase converter. The SPWM, a sine wave control signal in combination with a high-frequency sawtooth carrier signal, is used to trigger the power switches. Switching of switches in each leg are contrary when the top switch is on the bottom switch is off, and vise versa. For three-phase operation, the switching of each phase has a 120° phase difference with the next leg (phase). The power flows from the EV battery to the grid when there is energy insufficiency in the grid, or it needs ancillary service, and the converter operates in inverter mode. The converter operates in rectifier mode while the battery is charging.

The V2G bidirectional charger model works in both charging and discharging mode with a unity power factor that means no reactive power transfer. The current flow from the battery to the grid is assumed positive according to the connection of the current measurement block. The charging current is also negative, and this holds through all the simulation results. In the three-phase simulation result $\mathrm{V_{a1}}$, $\mathrm{V_{b1}}$, and $\mathrm{V_{c1}}$ is used to represent the AC voltage source for phase A, phase B, and phase C, respectively, and $\mathrm{V_{a2}}$, $\mathrm{V_{b2}}$, and $\mathrm{V_{c2}}$ is used to represent the AC voltages generated by the battery and converted during inverter mode for phase A, phase B, and phase C, respectively.

Table 5-2: Parameters in Figure 5.1 used in the Simulation.

Parameters	Values
AC voltage source	480 V
AC side inductor, L	5.5 mH
AC side resistor, R	10 mΩ
DC link capacitor, $C_1 = C_2$	1 F
DC side inductor, L_{DC}	5 mH
Battery capacitor, C_{DC}	1 F
Battery nominal voltage	500 V

The parameters resistor, inductor, and capacitor are selected based on the simulation test. The inductor in the circuit is used to reduce the ripple current, and the capacitor is used to reduce the DC-link ripple voltage. The capacitors used in this simulation are huge, which is not possible in practice.

The three-phase bidirectional AC-DC converter used in this simulation model is made up of six MOSFETs switches in parallel with a diode, and it is connected with the DC-link capacitor

(C_1 and C_2) across the DC side. The end of the converter is connected to the three-phase AC supply through a series resistor (R) and an inductor (L). All the elements and values used in the half-bridge single-phase AC-DC converter are the same, except they combine to make the three-phase here. The two switches in one leg operate in contrary mode, to avoid short circuit.

By controlling the pulse signal applied to the gate of switching inverter, the output voltage generated from the inverter is regulated. The SPWM (control signal) is compared with the high-frequency sawtooth carrier signal to produce the switching pulse to provide the switching gate, see Figure 5.11. There are several switching pulses with a different width in each half-cycle due to the high-frequency carrier signal. As shown in Figure 5.12, each generated pulse width changes based on the amplitude of the control signal (sine wave).

In the design of the bidirectional AC-DC converter, smooth mode transition between rectifier and inverter is essential. The EV battery pack need to manage a wide range of current in to and out from the battery depending on the state of charge (SOC) to maintain the battery healthy. For fast power transfer response, the transition between rectifier mode and inverter mode should be quick and smooth enough. The mode transition for power transfer between the battery and the grid is managed by changing the sine wave phase angle of the PWM switching.

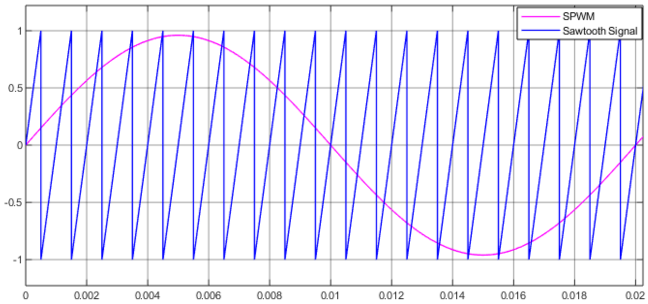

Figure 5.11: Sinusoidal pulse width modulation.

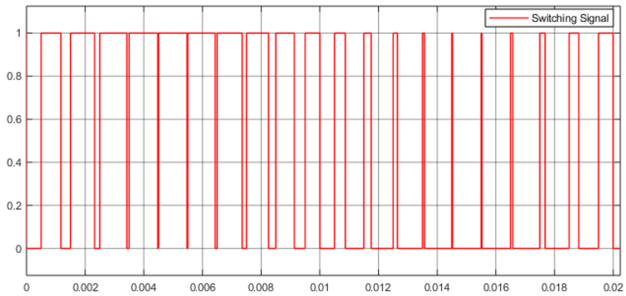

Figure 5.12: Generated gate pulse switching.

5.3.1.1 Simulation Result for Charging Mode

When the three-phase bidirectional AC-DC and DC-DC converters combined to make the full EV charging station, the converters operate in rectifier and buck mode respectively during charging mode. As mentioned earlier, the phase angle of the sine wave control signal in the SPWM controls the magnitude of the current and also the direction of flow. In the rectifier mode, the phase angle is negative during the charging of EV.

The AC voltage source is 480 V, and EV battery nominal voltage is 500 V DC used in this simulation model. The same to the single-phase, SPWM is used to control the power switching with a frequency of 25 kHz in the sawtooth modulating signal, and the simulation carried out for 4 seconds in the charging mode. The DC-DC converter operates at a constant duty cycle of 50%, and its operation is presented separately above. When the charging simulation carried out, the state of charge of the battery is set to 10%.

Figure 5.13 shows the simulation result for rectifier mode that the grid voltage and the current have 180° phase shift, which implies a unity power factor to ensure transferring only real power. The result presented is phase A from the three-phases, and it is the same in each phase, but a 120° phase difference between two phases.

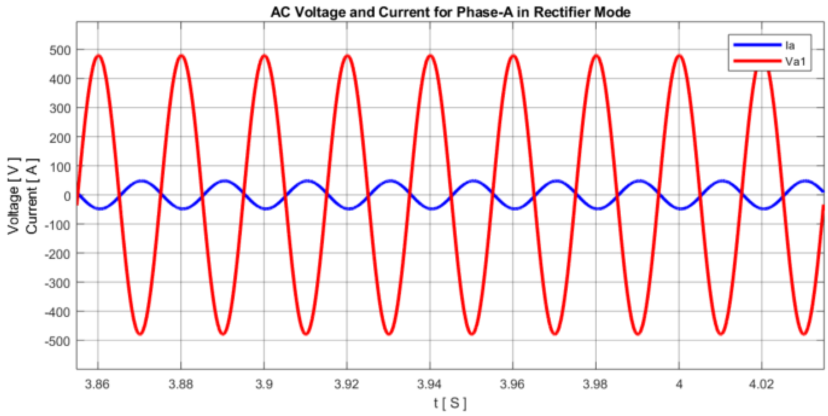

Figure 5.13: AC side voltage and current in phase A during charging.

Figure 5.14 and Figure 5.15 presents the three-phase voltage and current, respectively. Each phase in the three-phase current and voltage has the same amplitude and 120° regular phase difference between them. The simulation time is 4 seconds, and it has small dynamics in the current at the beginning. As can be seen from the figures, the screenshots are taken at the end of the simulation time.

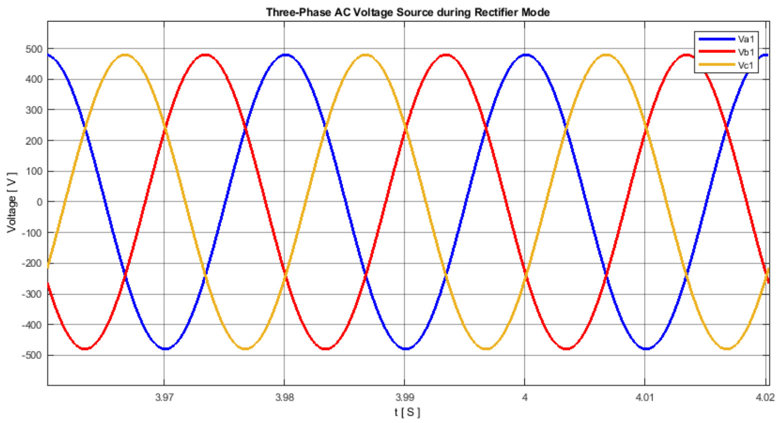

Figure 5.14: Three-phase grid voltages during charging.

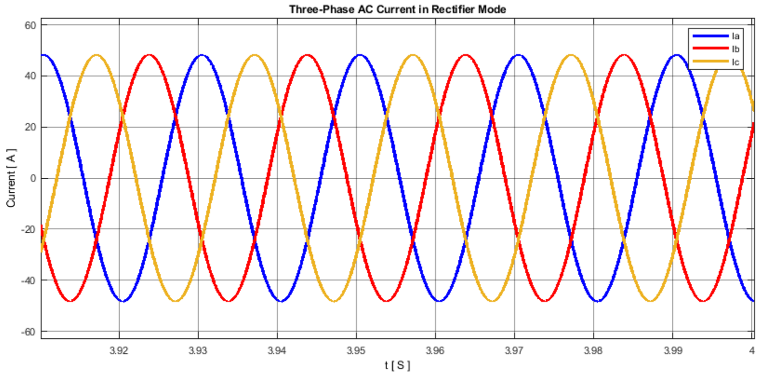

Figure 5.15: Three-phase grid currents during charging.

As mentioned above, the current flow from the battery to the grid is positive. The average charging current is shown in Figure 5.16, and it is clear that the direction of power transfer from the direction of the current flow. It is obvious the current flows from the grid to the battery during the charging mode, and the DC-link voltage during charging is presented in Figure 5.17.

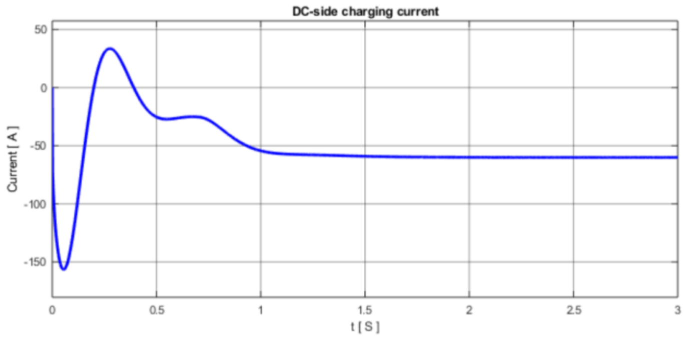

Figure 5.16: Battery DC charging current.

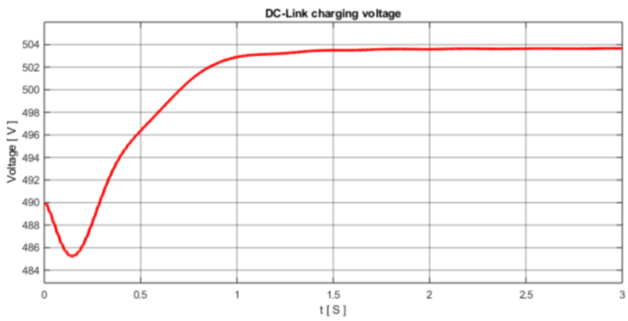

Figure 5.17: Center-taped DC link voltage during rectifier mode.

The simulation result in Figure 5.18 shows only pure real power transferring from the grid to the EV battery as the reactive power is zero, and the battery operates as a resistive load. The steady-state real power flow shows negative in charging mode because the charging current is assumed as negative. Essentially, as clearly displayed from Figure 5.16 to Figure 5.18, the charging current and voltage take almost 1.25 seconds to reach a steady-state in the charging mode.

Figure 5.19 presents the three-phase current and voltage for phase B, and it is clearly visible that the current for phase B (green color) and voltage (red color) shifted 180° from each other during charging. The current for three-phases are plotted, but the current and voltage in phase B should be compared. Figure 5.19 is presented to show that the two phases also have the same result with phase A, shown in Figure 5.13, except for the 120° phase difference between two legs.

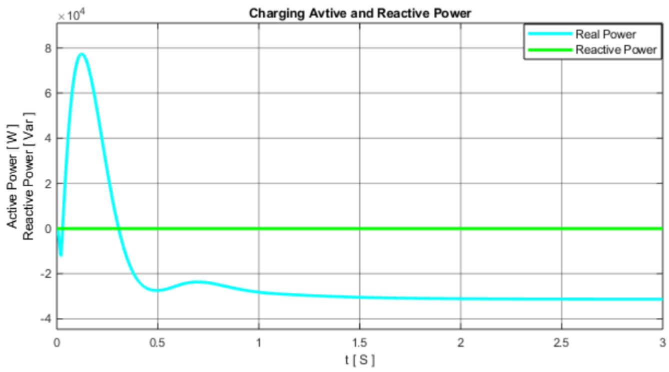

Figure 5.18: Active and reactive charging power.

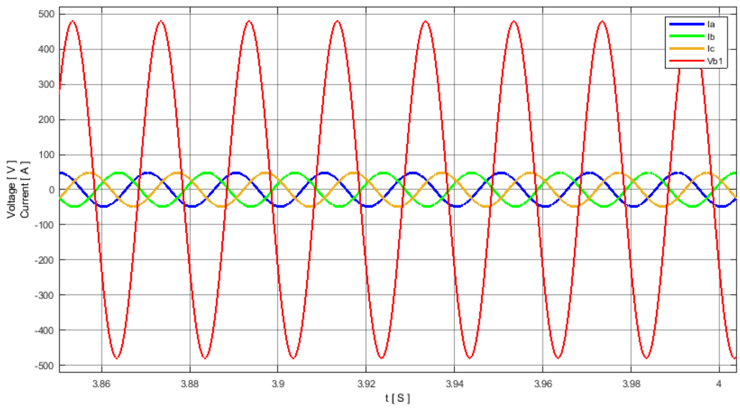

Figure 5.19: The three-phase current and voltage in phase B during charging.

5.3.1.2 Simulation Result for Discharging Mode

As the charging station model operates bidirectionally, this subsection presents the important part V2G application, the vehicle supply electric energy to the grid. When the EV battery is injecting power to the grid, the DC-DC converter works as boost mode to provide at a higher and fixed voltage than the battery nominal voltage to the AC-DC converter in inverter mode. The AC-DC converter operates as a voltage source inverter to convert the DC voltage to AC voltage at an appropriate amplitude and frequency, which is the same with the fundamental AC grid connected in the AC side of the converter. To change the operation between charging and discharging mode, it requires only to change between positive and negative the phase angle of the sine wave in SPWM for the bidirectional AC-DC converter, as stated above. As the phase angle was negative in the charging mode, here, the phase angle in the AC-DC converter is positive. The simulation results and screenshots presented in this sub-section are for discharging/inverter mode.

Figure 5.20 shows the voltage output from the inverter and the current in the grid at a steady state. The voltage and current are in phase, which is the opposite of the rectifier mode, as can be compared to Figure 5.13 (rectifier mode). The AC voltage generated by two-level three-phase in the inverter mode is the same in magnitude and phase with the voltage in the grid, as shown in Figure 5.21. The AC current, the fundamental AC grid voltage, the AC voltage converted from the DC voltage are in phase, which maintains a unity power factor for transferring real power the same to the rectifier mode, as displayed in Figure 5.21. If voltage and current are in phase, only real power is transferring [76]. As the phase angle controls the magnitude of current flow, the amplitude AC current also decreased when the phase angle is reduced by half as displayed in Figure 5.22, but it is more apparent in the DC side.

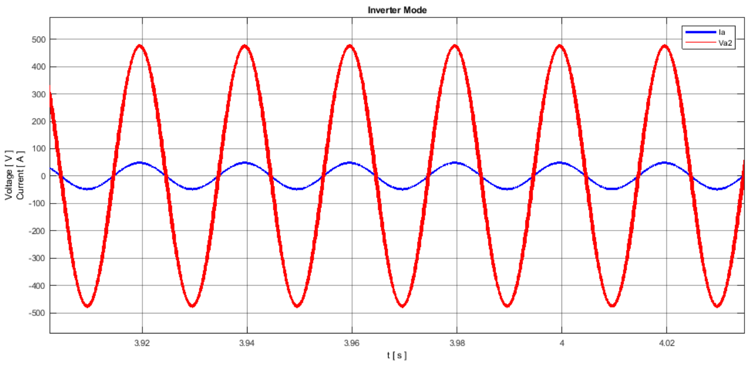

Figure 5.20: AC voltage and current converted by the bidirectional AC-DC converter during discharging.

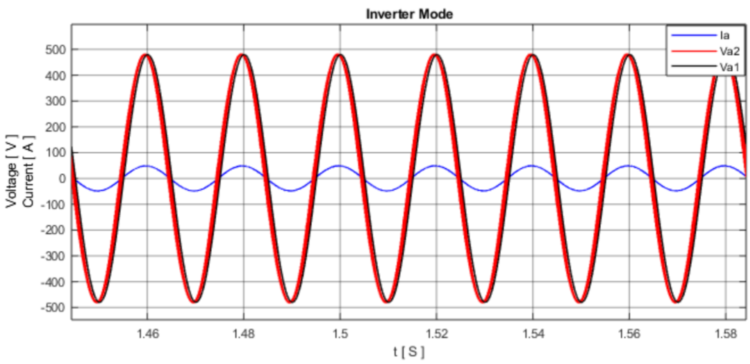

Figure 5.21: AC voltage generated by the inverter, AC grid voltage, and AC current (50 A).

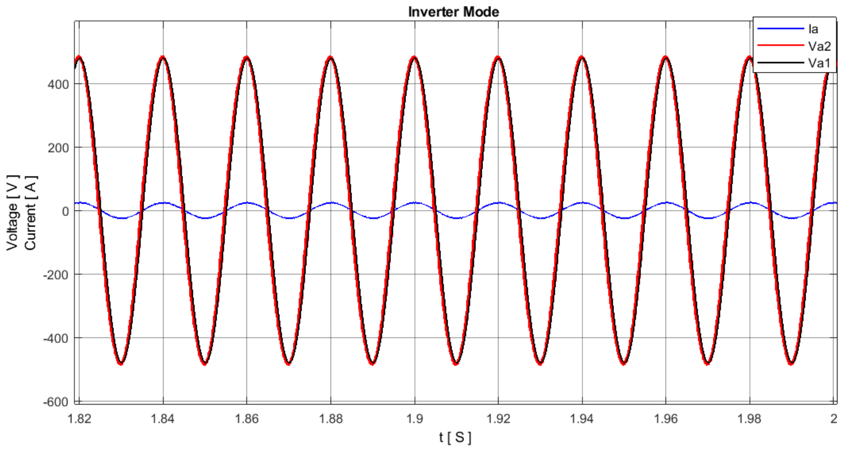

Figure 5.22: AC voltage generated by the inverter, AC grid voltage, and current (25 A).

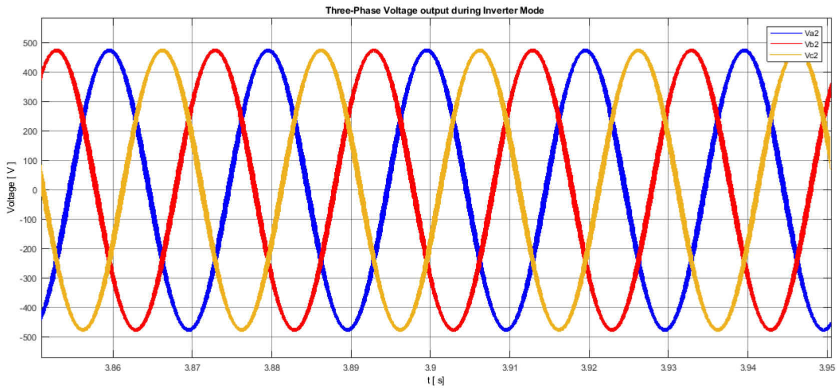

Figure 5.23: Three-phase AC voltage produced by the bidirectional AC-DC converter during discharging.

The three-phase voltage converted from DC to AC by the bidirectional AC-DC converter and the three-phase current are presented in Figure 5.23 and Figure 5.24, respectively. Similar in charging mode, each phase has the same magnitude and phase difference of $120°$ one phase with the next phase.

The DC discharging current is shown in Figure 5.25, and the result indicates the magnitude of charging and discharging current is almost the same, but opposite directions. As mentioned above, the current depends on the phase angle sine wave of SPWM. The simulation result in Figure 5.26 is when the phase angle is reduced by half from the result presented in Figure 5.25, and it is visible that the current is also lower by half. Similar to the charging mode, Figure 5.27 shows the center-tapped DC link voltage, and only active power is injecting from the battery to the grid as it can be seen in Figure 5.28. Similar to the charging mode, after almost 1 second, the discharging current and voltage reach its steady-state.

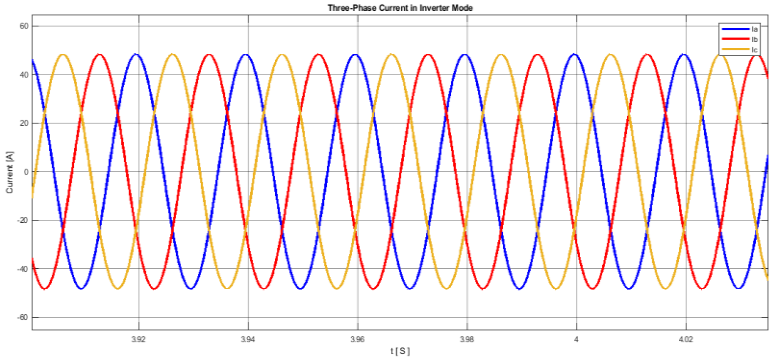

Figure 5.24: Three-phase AC current in discharging mode.

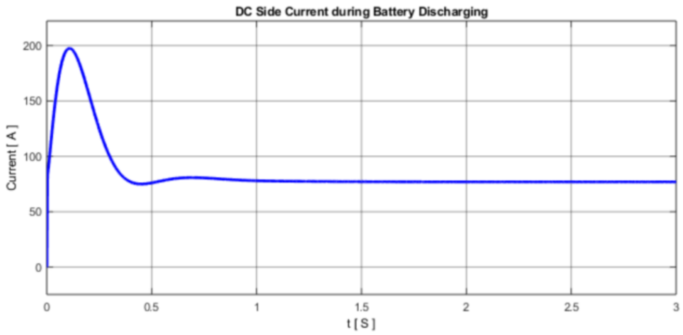

Figure 5.25: DC discharging current at phase angle 10°.

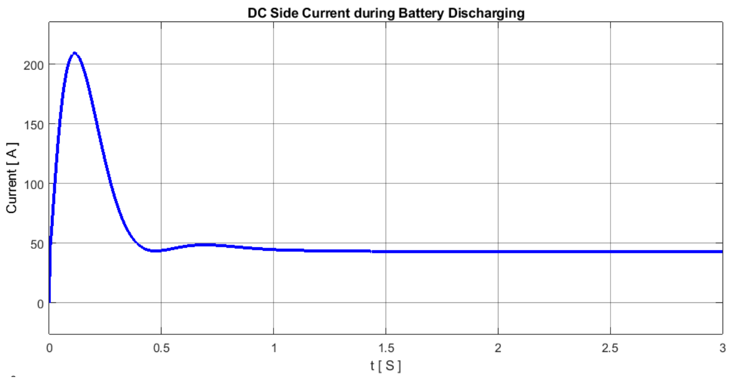

Figure 5.26: DC discharging current at phase angle 5°.

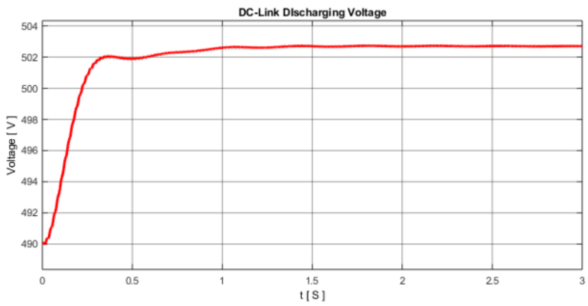

Figure 5.27: Center-taped DC link voltage.

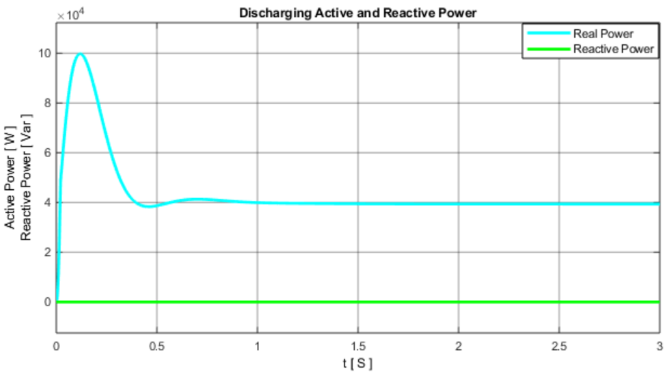

Figure 5.28: Active and reactive power injecting from the battery to the grid.

The simulation result for charging and discharging plotted in one figure. AC side of the converter, the voltage, and current for phase A in both rectifier and inverter mode are presented in Figure 5.29. The 180° phase difference in current for inverter and rectifier mode ensures the power flow reverses when the converter mode changes. According to the current measurement convention on the DC side, negative current for charging and positive current for discharging, as shown in Figure 5.30.

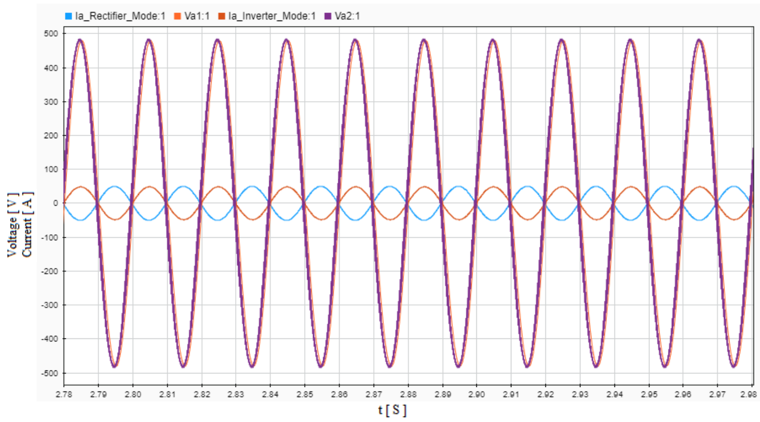

Figure 5.29: AC voltage and current for rectifier nad inverter mode in phase A.

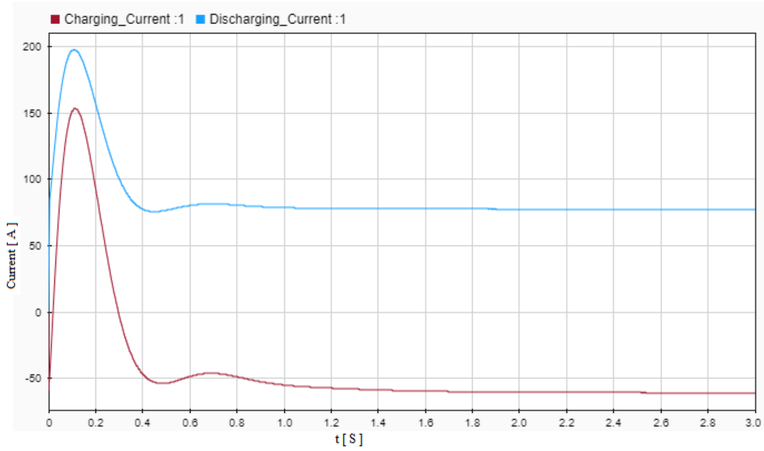

Figure 5.30: Charging and discharging DC current.

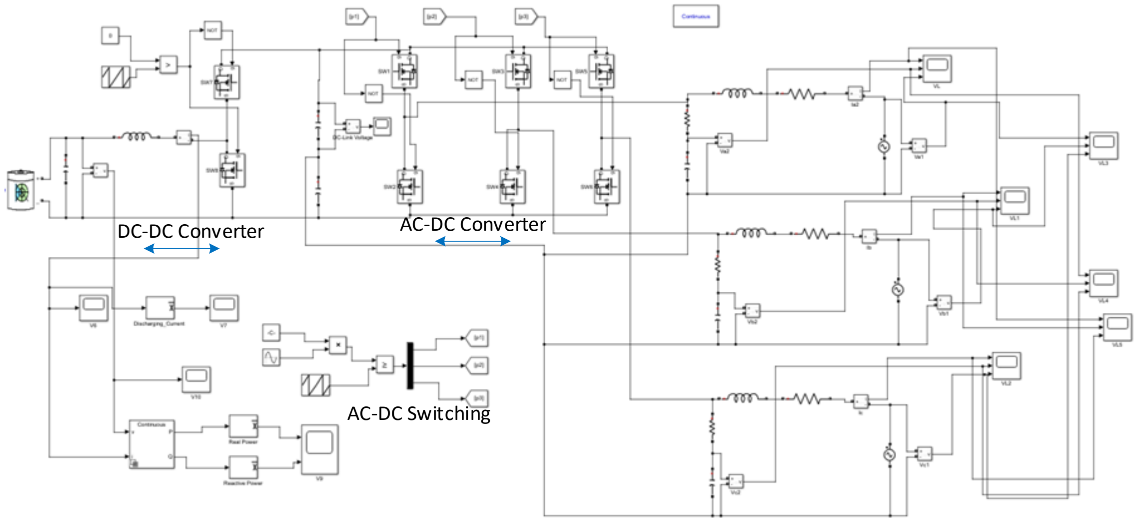

Figure 5.31: Simulation model proposed for EV charger without galvanic isolation.

5.4 Challenges of Bidirectional Charging

The advantage of the bidirectional charger is the capability to change the power flow direction instantaneously in the AC-DC converters according to the requirements. Despite all the plus side, there are some challenges in the bidirectional charging. The experience from devices such as phones and laptops shows Lithium-Ion batteries degrade with time. Similarly, in V2G technology, there is a concern about the several charging and discharging of the vehicle that may degrade the EV battery. A Lithium-ion battery used in EV has almost 5000 life cycle. One cycle of battery life is a single charge and discharge. When the battery is used in the V2G technology, the number of cycles is probably increasing, and it results in decreasing battery capacity. Battery capacity reduction implies the end of battery life. Only shallow discharging also improves battery life. Proper control of charging and discharging of battery required to raise the lifetime of the EV battery [77].

Despite all the positive side of EV, the distribution of EV is still facing obstacles, such as battery life, availability of charging infrastructure in rural areas. Also, the production of harmonics by EV chargers is another essential issue that affects the quality of power in the distribution system [30].

Another drawback of V2G is difficulty in meeting the technical regulations from the electric utility when power is exporting as there is no exciting system to receive power from distributed storage. Furthermore, although it is feasible to achieve the technical requirements for pushing back power to the grid, the implementation of V2G is delaying due to no markets developed previously. The aggregator and the electric service providers are different parties, and this can also lower the revenue and cause imbalance charging [53]. As well as it boosts the capital cost of the vehicle because the bidirectional EV charger needs a complicated installation and converter controller. To educate the technical part for customers, and their acceptance is essential. The EV connected bidirectionally to the grid always has communication. Therefore, most customers are skeptics of V2G technology due to security concerns in addition to the battery degradations. The eclectic utility or aggregator knows the customer’s location or routine. As a consequence, customers are worried about their security [30].

The application of unidirectional charging is in level 1, level 2, and level 3. However, the bidirectional charger is feasible in level 2 and level 3 because of the limitation of energy in level 1 charger [30].

5.5 Discussion

This subsection discusses the simulation result for the two-stage bidirectional EV charger model without galvanic isolation. The bidirectional three-phase AC-DC and DC-DC converters combine to make the two-stage two-way EV charging station model. The developed charging station is capable of power transfer bidirectionally to realize V2G technology. The first converter (AC-DC) performs as a rectifier during charging mode and inverter mode when power transfer from the battery to the grid, as shown in Figure 5.13 and Figure 5.20, respectively. The three-phase converter is provided with an appropriate phase angle to transfer only real power. The 180° phase shift in current during rectifier and inverter mode confirms bidirectional power flow. As stated above, the direction of power transfer is controlled by changing the phase angle of the sine wave (control signal) in the SPWM used for switching of the two-way AC-DC converter. Generally, if the phase angle of the sine wave is negative, voltage and current in the grid are 180° phase-shifted, and power transfer is from the grid to the battery, which is charging. If the phase angle of the sine wave is positive, voltage, and current in the grid are in phase, which implies the reverse power flow of the charging mode. Carefully sizing of series inductance, resistance, and proper parametrizing of the SPWM used to control the AC-DC converter can reduce the impact of the converter on the grid significantly. The sizing of inductance and resistance is estimated based on the simulation test. The simulation result for the grid side is satisfactory during battery charging and discharging to the grid.

The bidirectional AC-DC converter operates at a very high switching frequency in both modes, and this can introduce high order current harmonics. The added harmonics affect the power quality of the power system. Some devices taking power from the grid may not tolerate the harmonics because they require pure sinusoidal. Connecting large line-inductance can solve the problem based on the simulation test, but with increased cost and slower response time in the system.

The main objective of the bidirectional DC-DC converter is to provide voltage regulation, and it operates as buck and boost during charging and discharging, respectively. The ability of the converter for varying the charging and discharging voltage can help to use the charger for a variety of vehicles. The simulation result showed that by proper control of the switching duty cycle, the desired output voltage in the buck and boost mode is achieved.

Additionally, the bidirectional power transfer is visible in the DC side current, as the polarity of the current changes when the mode changes between charging and discharging. The conventional current flow from the battery to the grid is assumed positive. Figure 5.16 shows the negative charging current in rectifier mode and Figure 5.25 displays positive discharging current in the inverter mode, so this approves the capability of the model for two-way power transfer. By looking at both figures, the charging and discharging currents have overshoot and some oscillations at the beginning. Charging current is negative, but the state of charge of the battery and the size of the DC-link capacitor plays a significant role in the simulation result. In this simulation test, the capacitors are enormous, which takes some time to charge, and the current flow to the battery is delayed during charging. The state of charge of the battery was 10% when the charging mode simulation carried out, and the battery started discharging even if it is in the charging mode until the current start to flow from the DC-bus. If a smaller capacitor is used, the battery starts charging immediately, but the DC-bus ripple voltage increases. Hence, large capacitors are used despite the shortcoming at the starting of the simulation. The charging current is positive at the beginning of the simulation, although the negative steady-state current is given as an initial condition to the inductor. However, the initial transient is worse without providing initial conditions for capacitors in the DC-link and inductor on the DC side. Therefore, it is imperative the proper sizing of passive components and providing an initial condition of current for the inductor and voltage for the capacitor.

The DC charging and discharging current is also presented in Figure 5.30 together. From this figure, discharging current reaches, it's steady-state earlier than the charging current. Although all the parameters maintained in both modes, discharging current is higher than the charging current. The state of charge of the battery influences the discharging current. Another important criterion is the internal resistance of the battery for charging and discharging is different, and the internal resistance also depends on the SOC. The discharging current can be decreased by increasing the internal resistance, but it can reduce battery efficiency as more charging energy is losing. Many other battery specifications may affect the behavior of the battery, which requires further investigation. As the voltage during charging and discharging is equal, the power provided to the grid at a steady state is higher than the charging power to the battery.

6 Bidirectional Electric Vehicle Charger Model with Galvanic Separation

In the previous section, the bidirectional EV charger without galvanic separation is presented, and this section discusses the two-stage converters bidirectional EV charger simulation model with galvanic isolation in the DC-DC converter. The bidirectional AC-DC converter is the same as the converter used in part 5. Only the non-isolated half-bridge DC-DC converter replaced with an isolated full-bridge DC-DC converter. A bidirectional isolated DC-DC converter technology separated by the high-frequency transformer is used to integrate the EV energy storage battery with the DC-link capacitor, and the AC-DC converter connects to the grid. The galvanic isolation increases the safety, reliability, and power density of the EV charger [49].

6.1 Bidirectional Dual Active Bridge DC-DC Converter

The full-bridge isolated bidirectional DC-DC converter is consisting of four switches with an anti-parallel diode in each H bridge on both sides of the transformer and inductor is connected to the HV side, as shown in Figure 6.1. The transformer used in this simulation test is ideal, which means no losses in the transformer. As MOSFETs have low voltage and high current ratings, it is appropriate to use on the low voltage side, although IGBTs or MOSFETs can be used on the high voltage side. Therefore, MOSFETs are appropriate on both the low and high voltage sides of the transformer [47]. The MOSFET internal on resistance and internal resistance of the anti-parallel diode is set to the default values in this converter. The converter operates with a 50% switching duty cycle. The 50% duty cycle helps to avoid unequal turn on and off times of switches MOSFETs. The unequal voltage in each waveform may cause to produce a net DC voltage either in the Low voltage side or the high voltage side of the transformer. A DC-bias current can cause saturation in the transformer, which reduces the efficiency of the converter, or it may destroy the converter [48]. The diagonal switches in the high voltage side and low voltage side bridges turn on and off at the same time to get a square wave voltage from each bridge on both sides of the transformer. As mentioned in section 3, the phase shift angle in the high-frequency square wave between the primary and secondary sides of the transformer controls the amount and direction of the power transfer. The power transfers from the leading to the lagging bridge, and by reversing the phase shift between low voltage bridge and high voltage bridge, the power transfer direction can be easily changed. Increasing the value of the phase shift angle raises the current, and this results in increasing the power transfer by the converter.

The bidirectional isolated dual-active bridge converter produces AC square wave voltages on both sides of the transformer with a frequency of 25 kHz. The voltage connected to the bridge in the battery side is v_1 and v_2 with DC source. When voltage v_1 leads voltage v_2 the converter is operating in discharging mode, and as the delay is introduced in the DC voltage source side bridge, the phase shift φ is specified as positive. The converter works in charging mode when the voltage $v_1$lags voltage v_2 and φ is denoted as negative. When the phase shift angle is zero ($\varphi = 0$), the current flow is zero, which implies no power transfer.

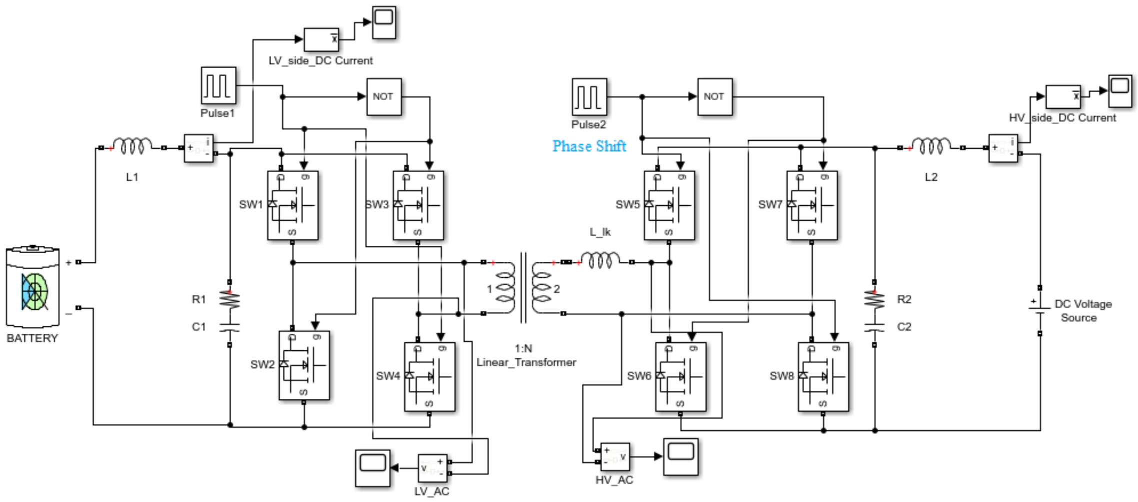

Figure 6.1: Bidirectional dual active bridge DC-DC converter.

The parameters used for the simulation of the dual active bridge converter in Figure 6.1 are summarized in Table 6-1.

Table 6-1: parameter used for dual active bridge converter.

Parameters	Values
DC voltage source	1000 V
L1, L2, L_lk	10 μH
R1, R2	10 $\mu\Omega$
C1, C2	100 μF
Switching frequency	25 kHz
Battery nominal voltage	500 V
Charging phase shift, φ	-2.16°
Discharging phase shift, φ	3.6°
Transformer turns ratio (1:N)	1:2

The simulation results of the bidirectional dual active bridge DC-DC converter shown in Figure 6.1 are presented from Figure 6.2 to Figure 6.5. As stated in section 3, the converter operates efficiently when the battery voltage and DC source voltage are equal or close to the transformer turn ratio. Figure 6.2 and Figure 6.3 illustrate the AC voltage waveforms in the low voltage (LV) and high voltage (HV) terminals of the transformer, respectively, and it is the same for both directions of power transfer. The amount of power transfer and its direction of flow is controlled by varying the phase shift. In Figure 6.1, the delay angle in pulse 1 is zero (battery side bridge), and the phase shift is set in pulse 2 (DC voltage side bridge). When the phase shift in pulse 2 is set φ = -2.16°, which tells the bridge controlled by pulse 2 is leading to the bridge controlled by pulse 1, consequently, the power flow to the battery. The average current flow on the low voltage side and high voltage side are shown in Figure 6.4. When the phase delay is changed to $\varphi = 3.6°$, the direction of the current flow is reversed, as displayed in Figure 6.5. It should be clear that the charging current is assumed to be negative, and the discharging current is also positive based on the connection of current measurement. If the phase shift increased from $\varphi = 3.6°$ to $\varphi = 5°$, the magnitude of current also increased, as presented in Figure 6.6, and it shows that the current increases almost linearly with the increasing of phase shift. Similarly, the current increases when the absolute value of the phase shift increased ($|\varphi|$) in the charging mode also. The magnitude of the current in the low voltage side is higher than the current in the high voltage side as expected for both directions to transfer the same power.

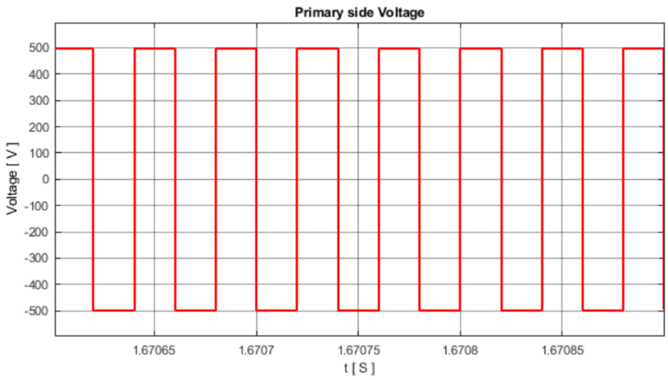

Figure 6.2: Low voltage side AC square voltage.

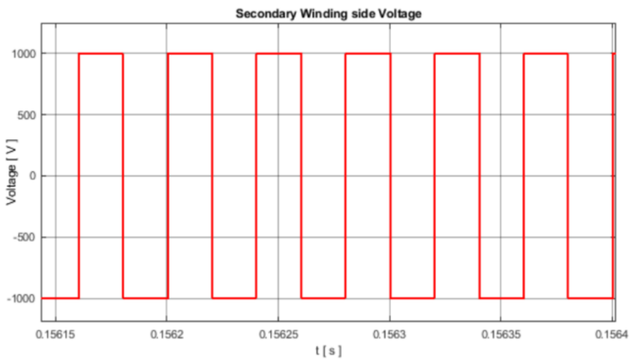

Figure 6.3: High voltage side AC square voltage.

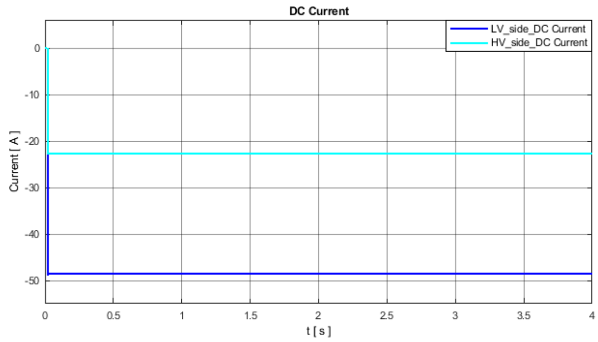

Figure 6.4: Average charging DC current in the LV and HV side$\varphi = 2.16°$.

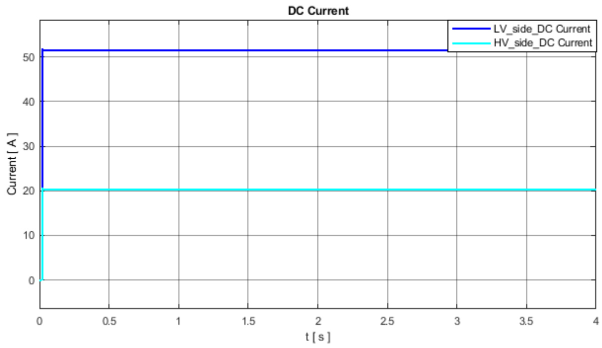

Figure 6.5: Average discharging DC current in the LV and HV side $\varphi = 3.6°$.

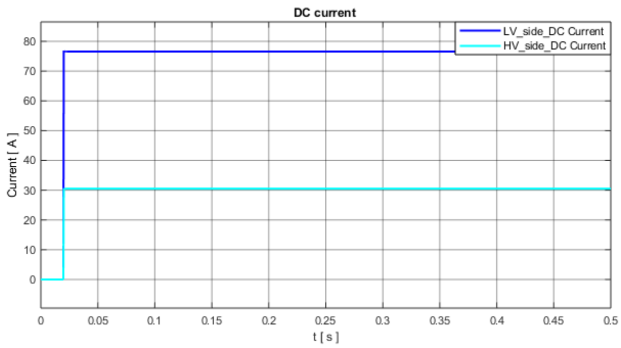

Figure 6.6: Average discharging DC current in the LV and HV side φ=5°.

6.2 Two-Stage EV Charger with Galvanic Isolation

The bidirectional dual active bridge converter is tested separately in the above subsection before connecting with a two-way AC-DC converter to make the EV charger model with the two-stage of converters. The direction of power flow is controlled by the cooperation of the switchings the bidirectional AC-DC and DC-DC converters. The operating principle and all parameters for the AC-DC converter are entirely identical to the converter employed in section 5. A SPWM (sine wave control signal and saw tooth modulating signal) is used for generating the switching signal to the AC-DC converter, and the phase angle in the sine wave controls the direction of power transfer. When the phase angle in the sine wave is negative, the converter operates in rectifier mode that means charging mode for the battery. Conversely, when the phase angle is positive, the converter works in inverter mode, and the battery provides power to the grid.

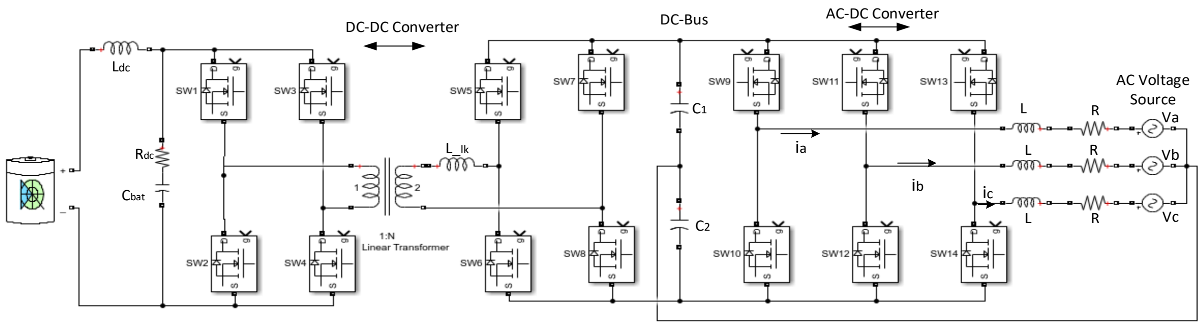

Figure 6.7: A two-stage bidirectional EV charger with galvanic isolation.

Table 6-2: Parameters used for simulation in Figure 6.7 the DC-DC converter part.

Parameters	Values
L_{dc}	10 μH
R_{dc}	10 $\mu\Omega$
DC-Bus capacitors, C_1=C_2	100 μF
Switching frequency	25 kHz
Battery nominal voltage	500 V
Charging phase shift, φ	-1.4°
Discharging phase shift, φ	2.4°
Transformer turns ratio (1:N)	1:2

In the dual active bridge, as discussed above, a high-frequency square wave is produced on both the LV and HV sides of the transformer. The bidirectional power transfer is achieved by phase-shifting the switching pulse of one H bridge with respect to the other switching pulse for H bridge (single-phase shift method), and the direction of flow is from the leading to lagging bridge. When the battery side bridge is leading, the power is delivering by the battery to the grid, and when the DC-bus side bridge is leading, the direction of power transfer is reversed, which the battery is in charging mode. Hence, for the EV charger model to transfer power in the desire direction, both the converters must operate to flow in the same direction. When the AC-DC converter works as rectifier mode, the battery side bridge in the DC-DC converter must be lagging to the high voltage bridge. And by reversing the modes of operation in both converters, the direction of power flow also changes. The simulation results for charging and discharging mode are presented below. As the parameters used for the AC-DC converter are the same as the previous section when the EV charger model with non-isolated is simulated, only for the DC-DC converter parameters are listed in Table 6-2.

6.2.1 Charging Mode

The bidirectional AC-DC and DC-DC converters are connected at the DC-link capacitors to form an EV charger model with a two-stage conversion. During battery charging, the AC-DC converter operates as a rectifier, and the phase angle in the sine wave (SPWM) used is -5°. In the dual active bridge converter, the power flow from the DC-link to the battery, which is from the high voltage side to the low voltage side. The varying phase angle for controlling power transfer is performed in the high voltage side switching. In this charging mode, the high voltage side is leading the low voltage side by 1.4°, which is given as -1.4° in the HV side, and the phase delay in the LV side is kept 0° consistently.

The focus of this simulation is verifying bidirectional power transfer using the single-phase shift control and, at the same time achieving stable 500 V half-bridge DC-link voltage is essential to avoid a negative impact on the AC side. Figure 6.8 shows the expected DC-link voltage with some initial transients. The DC-bus reaches steady-state around 1 second. During this simulation test, all parameters are kept constant, and only the phase shift in the dual active bridge is used to obtain stable DC-link voltage and the amount of power transfer. The mean charging current in the battery and the DC-link side is presented in Figure 6.9, and the negative current is only due to the connection of the current measurement. The current measurement is kept the same in the charging and discharging to see if the flow reverses when the mode changes. As the voltage on the HV side is twice the voltage on the LV side, but the magnitude of the current is higher in the LV side, which verifying constant power transfer on both sides of the high-frequency transformer. Figure 6.10 illustrates the AC voltage and current has a phase shift of 180° that confirms only real power transfer.

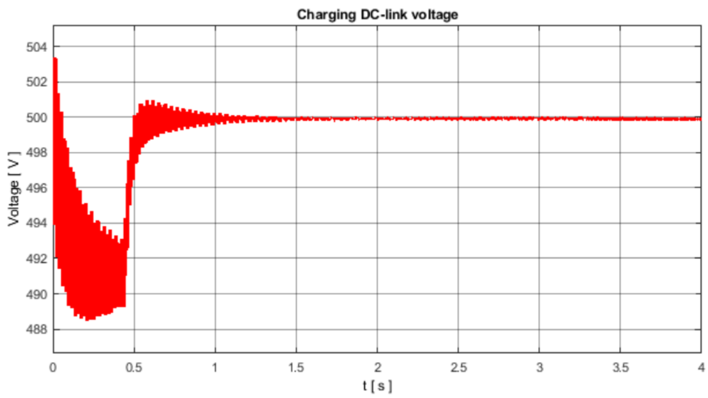

Figure 6.8: DC-link voltage during charging.

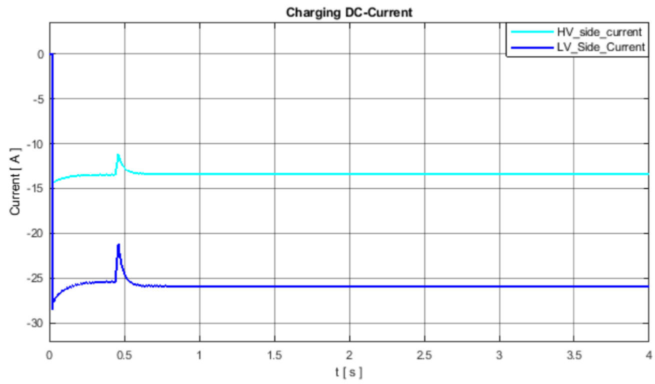

Figure 6.9: Average charging DC current in the high and low voltage side of the DC converter.

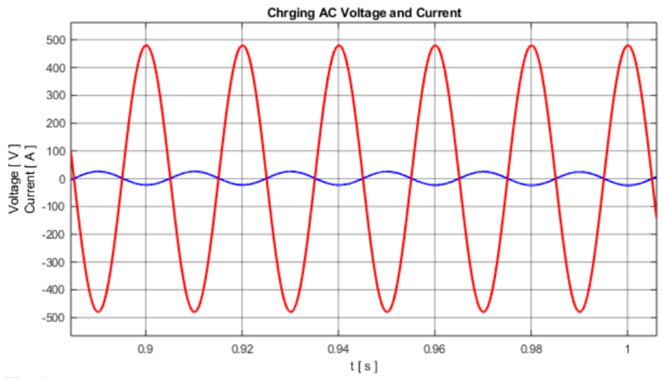

Figure 6.10: AC voltage and current when power flows from the grid to the EV battery.

6.2.2 Discharging Mode

For bidirectional power transfer, both the converters must operate to conduct in the same direction. Changing only the sign of phase shift angle in the HV side bridge from negative to positive in the DC-DC and AC-DC converters reverse the direction of power flow. The phase angle in the sine wave of SPWM for the AC-DC converter is kept the same magnitude as charging 5°, but changed from negative to positive. However, in the DC-DC converter, the phase shift angle is higher in magnitude than the charging to obtain the desired stable DC-link voltage, which is simulated with 2.4°. Based on the simulation test, if the DC-link voltage is higher or lower than 500 V, the voltage output of the inverter will not be synchronized with the AC fundamental voltage in the grid. Therefore, it is essential to increase the phase angle to obtain the required DC-bus voltage.

The DC-bus voltage provided to the voltage source converter is shown in Figure 6.11 when power is injecting to the grid with initial oscillation similar to charging mode. Similar to the charging mode, the DC-bus reaches steady-state around 1 second. The mean DC current in the HV and LV side of the dual active bridge converter is also presented in Figure 6.12, and this proves bidirectional power transfer as current flow is reversed compared to the charging mode. In the AC side, the voltage and current are in a phase see Figure 6.13 that means the current flipped 180° compared to charging mode, which verifies reverse power flow in the AC side also.

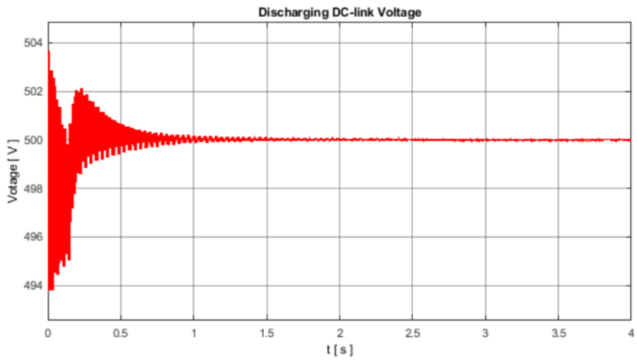

Figure 6.11: DC-link voltage during discharging.

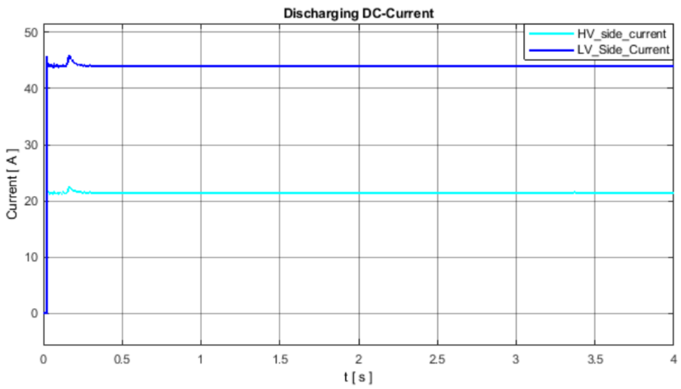

Figure 6.12: Average discharging DC current in the high and low voltage side of the DC-DC converter.

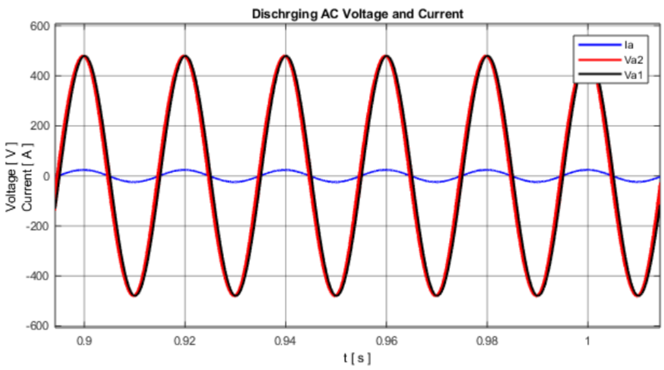

Figure 6.13: AC voltage and current when power transfer to the grid.

The operation of a dual active bridge converter with soft switching is one of the advantages mentioned above. Soft switching in a power converter is when there is zero or near to zero losses related to switching. When the voltage is zero, and the current is rising, this known as zero voltage switching. Figure 6.14 presents the HV and LV side voltages and the leakage inductance current to show soft switching. The switches are turning on and off at zero crossings. This screenshot is taken during discharging, which means power is flowing from the LV side to the HV side as the LV side is leading. The phase shift angle is visible from the figure below, even though it is tiny (the low voltage green color is leading).

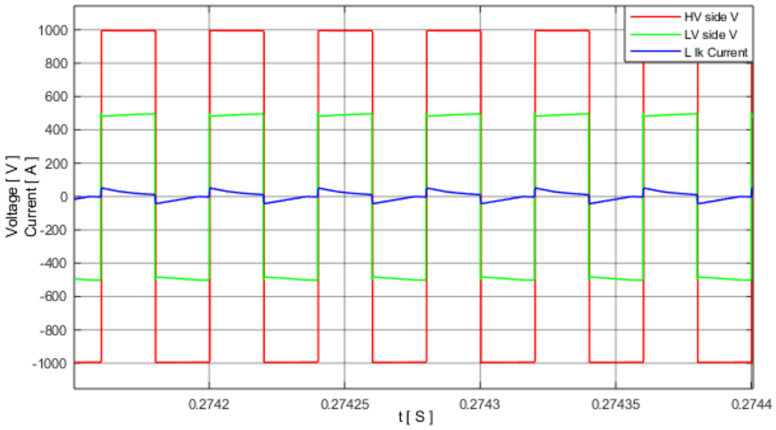

Figure 6.14: HV and LV side voltages and inductor current displaying soft switching.

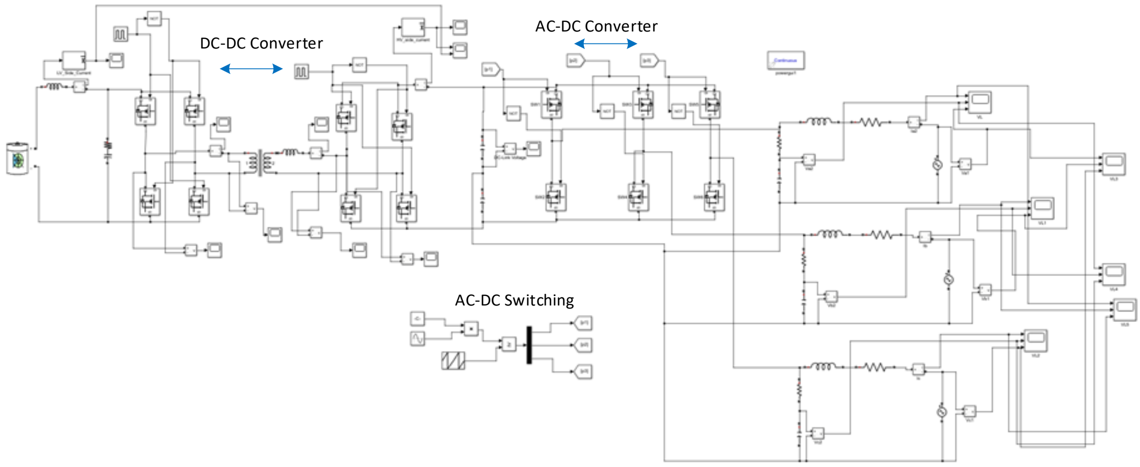

Figure 6.15: Simulation model proposed for EV charger with galvanic isolation.

6.3 Discussion

This section has presented the developing and simulation result of the bidirectional EV charger with galvanic separation. The overall results obtained with the proposed isolated dual active bridge converter are reasonable. The DC-link voltage gets stable to the required half-bridge 500 V after almost 1 second. Although there is some initial voltage oscillation, the range of the oscillation is acceptable, especially in the discharging mode. By increasing the capacitor value, the magnitude of transients can be reduced, but it will take a longer time to get stable. By controlling the phase shift in both converters, the current presented in the AC and DC side for charging and discharging approves the possibility of bidirectional power transfer using the developed two-stage conversion EV charger model. As the connection of current measurement is kept the same, in the DC side in charging mode current is negative, and when the mode changes to discharging, the current flow reverses, and it is positive. However, the discharging current is higher than the charging current as of the magnitude of the absolute value of the phase shift, $|\varphi|$ is larger in the discharging mode. Because the DC-link voltage requires a higher current to get stable, 500 V. The DC-link voltage has a significant impact on the AC current and voltage. Therefore, it is essential to obtain stable DC-bus voltage by increasing the phase shift. Different charging and discharging power transfer will not cause a problem as long as the charger can handle it.

7 Conclusion and Future Work

7.1 Conclusion

In this thesis report, the efficient way of charging EV form environmentally friendly energy sources and converter technology for bidirectional power transfer is reviewed. Also, the available standard EV bidirectional charger is investigated. According to the task description, a two-stage structure bidirectional EV charging station is developed and simulated separately with and without galvanic separation. The two-stage converter topology is selected due to the possibility of regulating the voltage.

In section two of this thesis, several ways of effective charging of EV have been presented. As the adoption of EVs is growing significantly, finding a way charging of EVs, which makes the transportation sector free from greenhouse gas emission, is essential. The focus of this task is to check out the possibility of charging EV from green power and economically viable from EV owners and the electric utility point of view for charging the EV. Encouraging shifting charging and time-based discounts in charging energy costs to meet renewable energy supply are necessary. Charging stations powered only from renewable energy is also the best solution.

In the third part, a literature review on converter technology for bidirectional transfer of energy between the EV batteries and the grid was presented with corresponding advantages and disadvantages. The idea of vehicle-to-grid is recognized as very attractive for integrating the grid and the EV for mitigating the unbalance between demand and supply in a power system. It can be concluded that the two-level three-phase converter is preferred from all the topologies depicted for the AC-DC converter. In the non-isolated bidirectional DC-DC converter, half-bridge buck/boost is a leading converter because of its high efficiency, high power density, and less bulky. Moreover, the dual active bridge is less complex from the bidirectional isolated DC-DC converter.

Currently, the available V2G connector as a standard charger is only the CHAdeMO DC charger. For the broader distribution of the V2G technology, it needs to be available from the other EV manufacturers with both AC and DC chargers, especially from CCS standards in Europe and North America. The CHarIN is working on developing the bidirectional charging in CCS standard, and it is expected to be available by 2025.

Lastly, the bidirectional EV charging station is modeled and simulated to facilitate EV charging and inject power back to the grid. The charging station consists of a bidirectional three-phase AC-DC and DC-DC converter, both isolated or non-isolated. Here in this work, the bidirectional EV charger model is implemented separately with and without galvanic isolation. The simulation results of both models are satisfactory, and the possibility of bidirectional power transfer with developed models is realized. The amount of power transferred by both models is similar, but discharging power is higher for both models. The charger with galvanic isolation has better safety, but with increased complexity to implement and control. The economic benefits for EV owners and the power system network and also environmental advantages are fascinating to the researchers' interest to work on the V2G technology. As a result, the bidirectional charging station is undoubtedly expected to play an essential role in the trend of electrification of the transportation sector.

Some of the services provided by EV vehicle with bidirectional charger are:

- Peak shaving is charging the EV battery at low demand hours and discharge the battery during peak hours.
- With demand increases from time to time, distribution and transmission need to upgrade. However, by increasing the number of EVs with bidirectional technology can be avoided or delayed the expense for expensive devices such as the transformer.
- It can be mitigated the intermittency of renewable energies like wind and solar power plants by implementing V2G technology.
- Spinning reserve in the power system is large generators operate at less than the maximum they can supply to supply power to the system during overload. A large number of EVs can serve as a spinning reserve to provide ancillary service and regulation in the power system due to the possibility that EVs can serve as a generation and a load.

7.2 Future Work

- Develop a prototype to validate the simulation results.
- Using an advanced control strategy, change charging, and discharging current when the state of charge of the battery changes, and also change the power factor to regulate the charging and discharging reactive power.
- Develop a model for battery charging from the grid and micro-sources, such as wind and solar.

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Appendix

Signed Task Description

University of South-Eastern Norway

Faculty of Technology, Natural Sciences and Maritime Sciences, Campus Porsgrunn

FMH606 Master's Thesis

Title: Bidirectional Power Transfer between Grid and Electric Vehicle Batteries

USN supervisor: Kjetil Svendsen

External partner: -

Task background:

Energy from environmentally friendly sources like wind and solar are not necessarily available at times when the power is needed in the grid. This means that the local generation of power does not reduce the peak power the mains distribution network from the utility company has to deliver. This means that it will not reduce the infrastructure cost. Also, since the energy will mostly be available at off peak hours, the energy will have to be sold at of-peak tariffs. If the energy can be stored locally, the energy can be supplied to the grid at peak hours reducing the peak load on the distribution network and at peak hour's tariffs. With an increasing number of electric vehicles (EV) available, the local battery capacity is increased and can be utilized bidirectionally. In the past, power flow was from the grid to the vehicle, only. However, the grid to vehicle and vehicle to grid power integration is gaining more interest in recent years. To accomplish this bidirectional electric power flow, bidirectional converters should be investigated.

Task description:

The thesis will contain different issues regarding:

- Survey of efficient battery charging possibilities from environmentally friendly sources, including the possibility of charging an electric vehicle directly.
- Survey of converter technology for bidirectional transfer of energy between the EV batteries and the grid.
- Investigate the automotive standards for charging and discharging EV batteries.
- Develop bidirectional EV charger simulation model
- If time permits, investigate options for galvanic separation.

Student category: EPE

Practical arrangements: -

Supervision:

As a general rule, the student is entitled to 15-20 hours of supervision. This includes necessary time for the supervisor to prepare for supervision meetings (reading material to be discussed, etc).

Signatures:

Supervisor (date and signature): Feb 4th 2020

Student (write clearly in all capitalized letters): OKBE KIFLE HABTE

Student (date and signature): 04/02/2020