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INVESTIGATION ON EV CHARGING STATIONS PENETRATION ON KAHRAMAA DISTRIBUTION NETWORK

BY

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ABSTRACT

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Title: Investigation on EV Charging Stations Penetration on KAHRAMAA Distribution Network

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The electrification of transport sector and the increasing demand of EV load supply from grid-connected public EV charging stations (EVCS) have imposed several challenges on the grid. Impacts include but not limited to increase in harmonic distortion, voltage drop, power losses, control and metering challenges. Hence, major part of the recent studies in literature of the field investigate these problems and search for possible solutions in order to mitigate these impacts on the public grid and distribution network. In this study, thorough investigation and comparison between various types of EV charging stations penetration impact on Kahramaa distribution network has been conducted. The research focuses on three major grid parameters; total harmonic distortion (THD) level, voltage drop and power losses at targeted buses where the EV charging stations are connected. Moreover, with penetration of renewable energy sources (RES), the EVCS-connected system performance is evaluated. Distribution network, EVCS and RES system are simulated using MATLAB/SIMULINK software. It is concluded in general that different EVCS brands have different impact on distribution network parameters and with presence of RES, these impact can be minimized.

DEDICATION

Firstly, thanks to Allah who provided me with the strength and time to work and complete this project.

This work goes to my parents, my wife and my extended family whom their continuous prayers guided me through my life.

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Chapter 1: Introduction

1.1 Background

The quantity of Greenhouse gas (GHG) emitted by the transport sector is the largest. The carbon dioxide (CO_2) emission in 2015 was calculated to be about 25% and 75% of it was emitted from cars and trucks [1] [2]. So, taking the information into account many projects have been started to reduce the CO_2 pollution produced by the vehicles.

As GHG emission in the EU is quite high that pollutes the Environment and transportation plays one-fifth in this respect [3]. European Union (EU) has set the targets to boost the share of renewable energy sources by 27% and to defeat GHG emissions by 40% until 2030 [4]. The research is aimed to increase the number of zero conventionally-fueled cars in the EU countries by 2050. Moreover, the main focus of researchers is to switch to waterborne transport and rail that will decrease the GHG emissions by 60% [4]

Many regulations have been made to switch to Electric transport to reduce emissions that include EC Regulation No. 443/2009 that intends to reduce the emissions to 95g CO_2 from the year 2020 [5]. In the USA, different standards have been made by Environmental Protection Agency (EPA) to reduce GHG emissions and for better fuel quality. It is expected that by 2025 the CO_2 emissions will reduce to 88.8 g / km that was 131 g /km in 2017 by the use of Electric Vehicles (EVs) [6]. The impact of EVs on the cities Madrid and Barcelona of Spain at 40% penetration rate of EVs causes the nitrous oxide emissions in between 11% to 17 %, and the air quality improvement of 8% to 16% for the values per hour [7]. Moreover, it has been studied that charging of EVs does not harm the environment instead of a factor caused by a decrease in nitrous oxide emission that causes ozone (O_3) concentrations to increase. The role of users to save energy by using EVs properly including a good usage of EV with the best driving behavior is very important [8]. The use of EV leads to many benefits that include the improvement of the environment that affects the lives of people directly. Depending on the best charging strategies used for EVs, the efficiency of electric systems can be improved [9]. The efficiency of Electric motors is about 95% that is significantly higher as compared to that of Internal Combustion Engines (ICEs). So, efforts are being made by the researchers to put forward the importance of EVs that has resulted in the reduction of GHG and a more friendly environment as compared to that offered by Internal Combustion Engines (ICEs) [10]. For such reasons, several countries announce that by 2030, considerable amount of their transportation sector will be EVs PHEV. Figure 1.1 shows EV growth on global scale and Figure 1.2 demonstrates EV market share for year 2018 [11]. Both curves indicate a sharp rise in the demand of EVs.

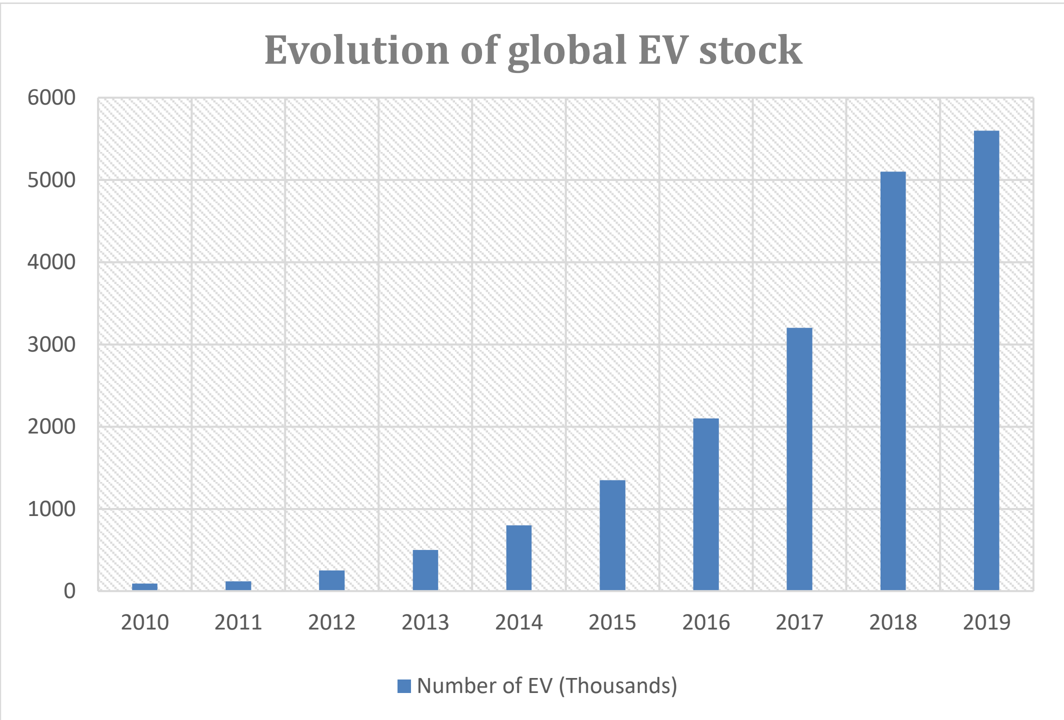

Figure 1.1.Evolution of global EV stock.

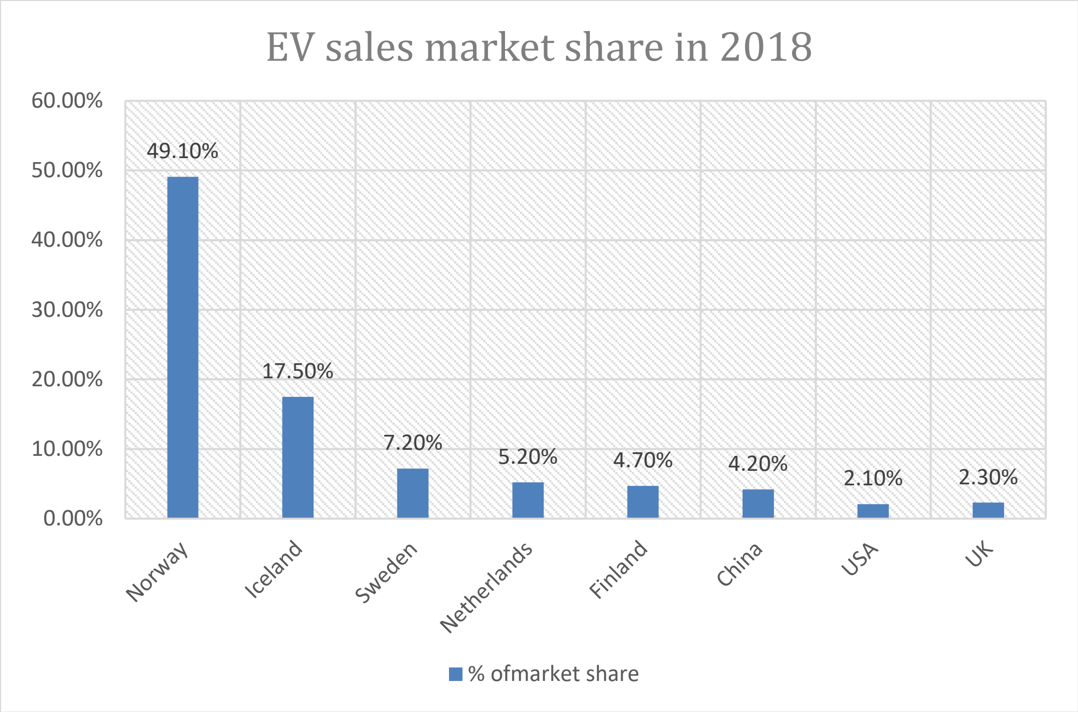

Figure 1.2. EV sales market share in 2018.

Nowadays, automobile manufacturers have recently introduced their EV brands such as Prius prime from Toyota, Leaf from Nissan e-Golf from Volkswagen and not the last Tesla X from Tesla company. In terms of Km range, they varied from 40km such as Prius Prime model to 506km Model S from Tesla. However, km range have direct proportional relation with the EV battery size. For instance, Tesla models batteries have capacity of 100kwh range while slow charging Zoe from Renault can only accommodate 33kwh battery size [11]. On the other hand, several Electrical companies such as EG, Schneider, ABB and others start producing different types of EV charging stations that have the ability of fast charging and hence can be installed in public places. For example, ABB Terra fast charging stations can charge up to 180kW and Schneider EVlink fast chargers series are designed to charge within half an hour with rate of 100kW [12].

As per the standard, there are three levels of charging labeled as level 1, level 2 and DC fast charging (DCFC) level [11]. The levels are classified based on their capability to charge EV battery within specified range of time. For example, level 1 and 2 are considered slow levels because their charging time usually in range of hours and EV charging stations of these level cannot be installed in the public places where the EVs do not have long waiting time. Nevertheless, they can be installed domestically or inside parking areas. Table 1.1 shows comparison between different EV brands and their related charging levels.

Table 1.1.Comparison of Several EV Commercial Brands

Vehicle model (Manufacturer)	model Year	Type	Battery Capacity (kWh)	Range (km)	Charging Time (0%–80%) (h)		
					Level 1	Level 2	DCFC
Prius prime (Toyota)	2018	PHEV	8.8	40	5.5	2.1	–
Leaf (Nissan)	2018	BEV	40	243	35	7.5	0.5
Model S (Tesla)	2018	BEV	100	506	96.7	10.7	1.33
Model X (Tesla)	2018	BEV	100	465	89	9.5	1.33
e-Golf (Volkswagen)	2017	BEV	35.8	201	–	6	1
Zoe (Renault)	2017	BEV	41	400	16	4.5	2.67
i3 (BMW)	2018	BEV and PHEV	33	183	13–16	5	0.5

Locally, Kahramaa has launched recently EVCS guidelines that will regulate the installation of EVCS in Qatar and to be integrated with the distribution network. In addition to that, several Schneider EVCS brand have been already installed in different places for trial purposes and as part of Qatar vision 2030, part of public sector school buses will be transferred to electrically-powered type [13].

1.2 Known and Well-Defined Existing Agents

Electrical control devices can still be differentiated by the design of their behavior. Certain agents are often referred to as non-regulated competitive agents [14]. This includes generators operating on wholesale electricity markets and suppliers operating on retail markets. Such types of agents are often referred to as network administrators or superiors. These agents work under private monopolies but incentive-based regulation. Transmission and distribution network providers function in natural monopolies. They act in what is called incentive-based legislation [15].

System delivery providers, transmission structure operators (TSO), and manufacturers stand of special concern. The TSO shall be responsible for providing a reliable operation at the local or nationwide level of transmission. The Power Systems Director shall be the vendor and operator of the supply grid. The distribution system operators (DSOs) cannot trade in electricity. They have network services only [16].

Supplier or manufacturer is an agent who provides energy to final consumers, to end-users of electricity. Delivery is assumed to be theoretically reduced in price by generation, delivery, and, in particular, by supply and retail. The DSOs are not permitted to deal in electricity. They have only networks and are fully regulated monopolies. The producer or manufacturer shall pay the DSO for the service, which, in exchange, supplies energy from the market.

In addition, the bill does not allow the final customer to resell electricity to an alternative final purchaser. Residential, private, or manufacturing companies are the final users. In certain nations, small domestic consumers used to buy electricity at a fixed cost [17].

1.3 Expected, Sketched, and Upcoming Agents

Besides well-known, well-defined electrical control system agents, two additional agents are required to be active in the infiltration of EVs into the system. The owner of the electric vehicle: an agent who owns the EV and wants power to charge the motor. It will also be able to offer other services to the infrastructure in the future. Any situation for a particular, Electric Vehicles Suitability Assessment (EVSA) will have device services from EVs under its power. There are two key options for the construction of charging structure: (a) individual charging areas for private or public access for owners of EVs; and (b) public charging areas with public access for owners of EVs. EV supply-aggregator is the EV supplier that delivers electricity to the user of the EV. In certain cases, EVSA will provide device services to the EVs under its jurisdiction. Two key options are suggested for the construction of charging networks and privately run charging facilities stations to be utilized for private or public connectivity for EVs members [18].

The charging point manager (CPM) believed that the owner of the land can install the charging infrastructure on private property. The EV charging station is the owner of the EV charger adapter that installs a range of charging points with varying operating options, in particular rapid charging modes, to provide this service to the community. The charging point manager can, under a contractual contract, buy the requisite electricity for charging its own EV or for reselling it to other EV owners linked to the power outlet. It is believed that the owners of EVs will install private property charging facilities.

As far as the law is concerned, CPMs that resell energy to a third party (e.g., the owner of EV) will be classified as suppliers or retailers. In customer parking stations, markets and places of public service, the construction of EV charging points would be costly to acquire a license to operate this type of operation. Where the need for a common benefit, such as a public place, is concerned, there is also a clear argument that the company should be regulated and charging points established either by the relevant DSO or by the competent authority in the region. In this situation, the facilities will be known like other grid costs and EV owners contracted with various EV providers should have universal access to charging points. In this scenario, the facilities will be considered as extra spending on the grid. In the case of privately held CPMs, Infrastructure and expenditure risks claimed by private agents can be raised.

1.4 Interaction and Coordination of Electric Power System Agents

The Gross plan for a system for the efficient incorporation of the EV battery into the grid, as allocated in energy infrastructure is under extensive studies. Research suggests that all entities of a physical energy distribution network are in the front row of generation, storage, supply, and end-user chain. In the literature of the field, it has been illustrated quite well how EVSA is merely a market player that promotes mutual ties between agents but does not own any financial properties. For Example, Current flowing from the TSO via electrical transmission properties to final analysis facilities. EVSA is essentially a market player that promotes business ties between agents and physical properties but does not own any of them.

Several criteria analyzed the success of penetration of EVs in the market that include, demography criteria, environmental criteria, economic criteria, energy criteria, and transport criteria [19].

The issue that caused a lack of interest among buyers is the EV batteries have low power and couldn't reach their destination. There should be stations and parking areas for the charging of cars. authors also discussed that there should be a display screen in the car to indicate that car is fully charged so that the other vehicle could be plugged in. Another method to increase the market share of electric vehicles is to choose an option of multicar. EVs are useful in covering short distances [20]. A survey was conducted and it showed a result that 82% of EV users in Sweden have more than cars. The early owners of EVs have been characterized as male (81%), between 40 and 45 years old, with high incomes and university degrees (77%), and mostly being part of two- or four-member families [21].

To overcome the barrier in the sale of EVs, the local and state governments launched many programs and the main aim was to give subsidy and these programs include more than 15 governments [22]. European government took measures to promote EV sales. Norway and Netherlands were the countries that have the highest shares. The government of California has decided to increase the number of vehicles from one million to 1.5 million by the end of 2025 [22]. Early adopters were young with high income and having an additional car. In Norway, a Climate Agreement was passed by the Norwegian parliament, 25% tax on the diesel and fueled vehicles to promote EVs. Then the attention was to the negative effects that EVs in Norway were used for the trips that could be covered by walking or cycling. But 41% of the buyers bought EVs for saving money in Japan where the national manufacturers were given priority and the cars sold were manufactured in their own country [23]. Women of Japan were more interested in buying EVs because they were environmentally friendly. The main hurdle for the buyers was the high prices of EVs. Overall, the EVs have a positive impact on the environment and they are novel in technology. Few buyers still have misconceptions about EVs and they need to be educated of the latest technology. The present market is facing a lot of hurdles regarding EV penetration. The costs of EVs are also quite high in markets. Many countries are working against the barriers in the ways of EVs penetrations into Electric Vehicles Charging Stations and the effect of EVs on Electrical systems is also a great consideration. Electric vehicles are the future asset of upcoming markets and they will be available in markets of every country that would be interested in an environment-friendly world.

1.5 Thesis Objectives

The main objective of this thesis is evaluation of several EV charging station topologies integration into the distribution network. Moreover, grid electrical parameters such as total harmonic distortion, voltage drop and power losses to be investigated in order to compare the results with international and local standards. Finally, Renewable energy sources to be integrated into the power system to mitigate the impact of EV charging stations on the grid

1.6 Methodology

Firstly, extensive literature review is conducted to determine the gaps in the research and the most urgent needs for the public grid utility regarding the integration of EV charging stations. Secondly, MATLAB/SIMULINK software has been used in order simulate several types of EVCS based on fast charging requirement and Kahramaa specifications. Thirdly, Kahramaa buses distribution network branch to be simulated using MATLAB/SIMLINK software and Kahramaa specifications.

Fourthly, the simulated EVCS have been connected into Kahramaa emulated distribution system and THD, voltage drop and power losses at targeted bus are analyzed. Finally, PV system is simulated and integrated into EVCS-connected distribution system

1.7 Thesis structure

Chapter 1 gives an overview of transportation sector current challenges due to high levels of air pollution. EV and EV charging station industry and the related energy agents have been discussed thoroughly. Moreover, thesis objectives and methodology were described briefly.

In chapter 2, extensive literature review has been conducted and the major research directions have been identified regarding Grid-EV interactions and the related economical and technical impacts.

Chapter 3 focuses on modeling and simulation of EV charging stations using MATLAB/SIMULINK software where several types of rectifiers and DC-DC converters have evaluated.

The simulated EVCS have been integrated into the grid in chapter 4 in order to evaluate distribution network performance in terms of harmonic distortion, voltage drop as well as power losses.

In chapter 5, a single low voltage feeder is selected for investigation with integration of renewable energy source.

A comparison analysis between medium voltage and low voltage feeders in terms of total harmonic distortion is conducted in chapter 6.

Finally, thesis is concluded in chapter 7 with main challenges in the present works and how it will be tackled in the future research

1.8 Summary

In this chapter, a brief look at the current level of air pollution levels around the world is discussed and how the countries and related organization are introducing regulation in order to mitigate emissions limits. Moreover, the current role of the crucial players in power systems is discussed from generation, transmission to distribution agents. In addition, new agents have emerged with rising of EV markets such as distributed generation providers and charging point managers imposing new challenges on the government regulatory boards. On the other, hand several commercially available EV, standard charging levels and Kahramaa new EVCS guidelines had been discussed.

Chapter 2: Literature Review

2.1 Introduction

Studies in in the field of EV-Grid relations have been investigated from different perspectives. Some of the papers are focused on the optimization of the deployment and operation of EV charging stations in order to minimize a specified objective functions that may include but not limited to cost function, network losses function or travelled distance. In addition to that, other studies search the process of charging and the optimal time under the category of charging strategies that target minimizing the impact of charging on grid demand in order to avoid the peak time. Furthermore, the impact of EV charging stations on electrical parameters such as harmonic distortion, voltage limits violation and thermal range of grid components is one of the intense area of research in grid-connected EV charging stations studies. However, some papers choose to focus on EV load modelling and study the effect of different models on the distribution network

2.2 Optimal Placement & operation of EVCS

Optimal placement of Electric Vehicle Charging Station (EVCS) is a basic need of present time as the world has been revolutionized and have great attraction towards the Electric Vehicles adaption. Many researchers have done great work towards EVCSs optimal placement and operation, some of the works are reviewed in this chapter. A solution had been proposed by Luo et al. [24] to place EV charging station along with providing a balance to the owner of EV, owner of charging station, and the operator of the power grid. A competition has been organized as a Bayesian game that helps to solve the policies for the service providers. The research had also focused on simulation-based results based on EV Virtual City 1.0 on Repast taking, San Pedro District of Los Angeles as a case study. The results of the simulation indicated a cluster to separate the charging stations by service providers, but the charging stations need to be placed according to Electric vehicles traffic flow consistency. Behdad et al. [25] divided the EVCS placement process into four modes with two uncertainty variables using a two-step solution based on Linear Programming Technique via GAMS (general algebraic modelling system) software. The modes help the EVCS location in medium voltage CIGRE network with optimal dispatch. The results indicated the percentage of perfection of the EVCS placement. Mehmet et al. [26] developed four steps approach to place EVCSs at optimal locations. The work is divided into two phases where in the first one the best geographical location was indicated and the provided information was mapped in the second phase using GIS (geographic information system) software for the grading of the indicated sites. In the third step, graded sites are prioritized by using fuzzy AHP (Analytic Hierarchy Process) and best EVCS locations are scored using TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) techniques. The results were suitable for the whole wide world as found in research. a case study of Ankara, Turkey also included. Andrenacci et al. [27] used the data from an old type of conventional vehicle in Rome and based on the analysis, the data provided a gateway to switch to the EV. The data was formed according to an urban area and efforts were made to apply it to the sub-urban areas to create an optimal location for EVCS. However, the research was the first step ahead as it did not account for important factors like the urban topography, national and European policies and did not consider any interference with the electric network, Moreover, the paper did cluster analysis on the location-based charging levels best infrastructures based on demand-side management. Aljaidi et al. [28] used Mixed Integer Linear Programming (MILP) technique to formulate the problem of elevation between the location of EV and EVCS and the discharge rate of EV to reach EVCS was considered here.

The Branch and Bound (B&B) algorithm was used to solve the problem. The research deduced the results that along with positive elevation of EV and EVCS difference, energy consumption of the EV increases. The varieties of charging station capacities were considered in that research along with the variation in elevation slopes. A best review for EV location plans was shown by Kizhakkan et al in [29].

2.3 EV Charging Strategies

The charging strategies of electrical vehicles are of great importance as they can enhance their efficiency and in return providing a green environment. Harris and Webber [30] studied EV charging and its effects based on their region and observed unscheduled energy charging in different scenarios. authors found the results that unscheduled EV charging caused variation in peak loads and the studies were effected by regional factors. Kong et al. [31] had shown a survey of preexisting Plug-in hybrid electric vehicles (PHEVs) charging strategies. The paper categorized the schemes as smart schemes, bidirectional charging, indirectly controlled, and uncontrolled schemes. The survey resulted into some important factors that included standardization of the evaluation model for charging scheme evaluations. The charging equipment designs should be improved. Storage options should be enhanced and power loss should be minimized. Zhang et al. [32] considered charging station to study delay-optimal charging scheduling of the electric vehicles (EVs) at different charge levels. Markov decision process (MDP) was proposed to solve the problem in which average cost constraints were used to perform an optimal scheduling to decrease any uncertainty during charging for EV. The sources used in the paper to charge EV were renewable energy devices and power grid. Razeghi and Samuelsen et al. [33] found that peak charging of EV played crucial role in several environmental and power issues. Salah et al. [34] suggested that EV penetration could cause power system losses and power quality disturbances.

To avoid these problems one can reduce the loss by following the proper charging strategies that can make the system stochastic and reliable. Based on the literature, Liu et al. [35] suggested an active response strategy to provide the best connection between EVs and grid systems. the impact of EV penetration is analyzed in the system. Based on the analysis it was deduced that EV charging strategies should be taken into consideration along with the penetration of EV in the system. Hajforoosh et al. [36] proposed a particle swarm optimization-based algorithm to represent several EV charging scheduling for charging profiles of a 5 minuets time slot to provide customers a high satisfaction level along with the grid constraints. Particle swarm optimization used by Yang et al. [37] to provide good satisfaction levels to EV users along with optimized cost for the grid operators penetrated with EV through different charging strategies along with best charging time intervals concepts. Villalobos et al. [38] studied the different charging strategies with higher efficiencies in EVs. Esmaili and Goldust [39] worked on the charging strategies of single-phase EVs through three-phase distribution systems. They applied an objective function for energy purchasing costs. Grid losses over the period due to charging losses were applied to the objective function along with a multi-tariff pricing environment. Qian et al. [40] worked on Charging demands that were predicted by using a demand calculation methodology for interconnection between grid and EV that was stochastically expressed for the state-of-charge (SOC).

2.4 EV Impact on Distributed generation (DG)

Emin et al. [41] had done an investigation on the impact of EV on 37 bus DG. The results had indicated that the node suffers voltage drop when the DG loaded. The voltages at different nodes were measured and different readings were taken under different EV locations and integration at different rates.

The search has opened a gateway towards the EVs sharing irrespective of their location. The model proposed by Sausen et al. [42] studies EV type, battery capacity, state of charge, on-board charger level as well as fuel consumption to forecast the EV energy demands. The EV demand forecast model was used to check the performance of the distribution transformer at different EV integration scenarios. When the penetration of EV in the system reached 50 percentage or higher, the distribution transformer was overloaded. The research by Rodrigo et al. [43] was focused on the implementation of coordinated charging networks. The EV penetration was indicated by the operator of the system and based on charger location and the load, it had decided to allow the penetration or make some other suitable decisions regarding system health. As the penetration increased to the nominal level that was described in the paper to be 40% the distortion in distributed network increased. Yong et al. [44] Studied that with the increase in EV penetration, the load on the distribution network increases and if it does not remain in the standard range as described, the system went through unsatisfactory circumstances. The study by Vaisambhayana et al. [45] was focused mainly on the solution to the problems produced due to the EV at the distribution side. The search results focused on the EVs increase and the overloading produced by it. The scenario of Singapore was taken in the studies. Moreover, the study also focused on the charging levels like single, double, three-phase, and fast charging DC and the related impacts on the distribution networks.

The increasing impact of EV penetration on the distribution grids of Norwegian was studied by Lillebo et al. [46]. a household meter is used for load flow analysis with the optimal location for the assessment of the fast charger in the grid. The aim was to minimize the grid losses and voltage deviation. The reactive power deviation due to the charger was investigated.

The results showed that the weakest cable would be the victim of the EV penetration over 20 percent. Moreover, a reduced reactive power was found at the fast charger. Dogan et al. [47] studied the impact of charging strategies of EV during peak hour charging. The Experiments were made at different penetration levels of EV and at different modes of charging. The results obtained from simulation results have shown that EV had a great impact on the PV buses. Different EV strategies were examined to get an improved system load factor. In short, EVCSs have several impacts on the grid and these effects can be categorized into negative impacts such as increase in demand and overloading. On the other hand, integration of EVCS may benefit the grid in several ways like improving power quality, regulating voltage and frequency and not the last supporting the grid during peak time. Flowchart summarizing the EV impact on distribution network is given in Figure 2.1 [11].

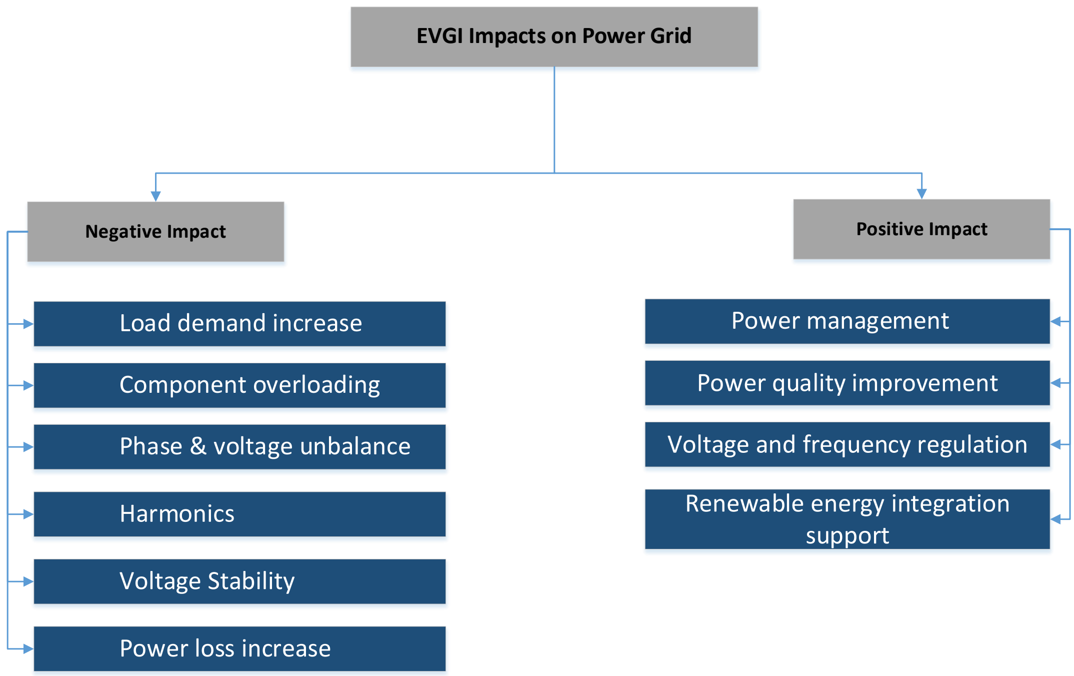

Figure 2.1. EV impact on power grid.

2.5 EV Load Modelling

Wang et al. [48] Worked on the large-scale penetration of the EVs in the power system as moveable charging loads. The random nature of the EVs was emulated by a driving pattern model. Different variables were made based on driving time, charging durations, and parking hours. Based on the EV charging at corresponding stations, an average of EV charging loads was measured by using Monte Carlo simulation (MCS). The results indicated that parking and non-parking EVs had shown variation in charging loads based on the location variations. The characterization of the EV load of a large number of EV units was done by Islam et al. [49] based on the constant current and constant voltage portions taking State of Charge (SOC) constraints under consideration. The results of the characterization had shown that EV load depended majorly on SOC. Another major aspect of the paper was the comparison of EV charging impacts for the case study of the University of Queensland's network. The charging behavior of EV was considered by Shukla et al. [50] to provide an appropriate load modeling. Based on EV charging characteristics, single and multi-stages time-variant coefficient of ZIP (Zero-inflated poisson) and exponential load model were studied to design the voltage dependency scheme. The ZIP load model was used to solve the problem by Quadratic Programming and exponential load model for solving the problem of Differential evolution. The study by Dharmakeerthi et al. [51] was focused on a model to handle the EV load taking the EV charger as well as battery into consideration during dynamic stage. The results of the research were based on the EV loads that had a massive impact on the damping performance of electrical as well as mechanical modes of the system that contains the EVs. The performance of EV load was checked by Haidar et al. [52] making a ZIP load model that was based on ZIP parameters. The ZIP parameters were taken from EV load data. The model had a great contribution toward the EV charger load penetration impacts on the system.

Moreover, the model has gone through the phase of comparison with the constant power load model by taking EV load data indicating that the analysis done based on the ZIP model was quite sound and provides a more realistic impact of EV charger penetration on the power grid. The work was done by Xie et al. [53] to establish the model mathematically and it had been based on the power consumption in the subsystems of the grid that was produced due to charging applications of EV. The best class (class 1 station based on the Beijing local research standards on public EV charging station) charging station was taken into the research. The results of the simulation were analyzed and found credible.

2.6 EVCS Impact on THD Level

A switched filter compensator (SFC) was proposed by Mohammed et al. [54]. The compensator was in connection with the battery charger through its AC side to find the best solution to the harmonic distortion that propagates into the electrical systems. The compensator had two parallel capacitors connected in the series arm filter to remove the harmonic distortion that will automatically enhance the charging power factors by reactive power compensation. The MATLAB and SIMULINK were used in this research. The results had ensured the least distortion by harmonics and the increased power quality had been achieved by using the SFC along with charging equipment for EVs. Harmonic analysis was carried by Rodrigo et al. [55] in a low voltage distribution feeder by modeling a charger using MATLAB with detailed analysis. It was concluded from the results that EV penetration has huge impacts on the feeders and the results were taken at multiple scenarios with the charging at different load levels. The work by Megha et al. [56] was focused on the analysis of harmonics and the distortions caused by them in charging stations. The research used buck-boost converters to simulate the charging stations.

The impacts of harmonics on the charging station were studies through the results of the simulations. The ripples were also analyzed during the research. The Total Harmonic Distortion (THD) produced by EV had been studied by Yijun et al. [57]. The paper had taken transformer, overhead transmission line, commercial area, and photovoltaic (PV) system as different scenarios of the electrical system under test and performed the analysis using PSCAD software. The analysis was made at different plug-in and plug-out conditions for the EVs focusing on THD influence. The paper provided some good suggestions to the EV owners and the customers to take into consideration and hence that will lead them to pave a way towards decreased THD level. The suggestion will improve the power factor along with a wide range of EV penetration in the system. The research by Shafad et al. [58] used buck converter to achieve different modes in Charging Stations. Moreover, a passive filter was used to decrease the impact of harmonic distortion in the system including EVs. The research used MATLAB/SIMULINK to design the circuits and to analyze the data including passive filters. Different modes of CS were used to analyze the data and to find the optimal situations where the harmonic distortion got decreased. The research results were satisfactory and accomplished the requirements of IEEE 519 power harmonic standard by achieving optimal harmonic levels with optimum passive filters. The impact of EVs penetration concerning the frequency levels was studied by Torquato et al. [59]. The data were collected for different EVs that were charged through different CS and the charging was done under different scenarios that include residential and commercial, slow-fast charging levels.

The analysis performed on EV penetration and charging at different frequencies concluded that at low frequencies harmonics effects were decreased by 4 percent while for high frequencies, it was found to be 1 percent. The study still needs a great focus as the results were not including the concerns of the utilities whether such distortion has any impact or not.

2.7 EVCS Standards

The predictions have been made on the energy and EVs role for the upcoming years. International Energy Agency (IEA) has set the target for EV products to 548 million by 2040. The role of EVs will expand through the world as predicted by the Energy outlook [60]. For the EVCS, the available standards include: IEEE1547 that is for the interconnection of DGs like EVs with electrical power system. The standard is responsible for the operation, safety, and testing of distributed energy sources that include EVs too. The standard applies to all the technologies having 10MVA or less capacity [61]. UL standards are also built for the integration of EVs into the system. The most considerable standard of UL among all is UL 1741 that specifies the protection systems and their precautions when the EVCS have to be installed into the system. UL standards are subcategorized into different codes like UL 62109-1, which are specified for different functions. Moreover, the safety of any equipment is a priority, and NFPA standards focus mainly on the safety of the EVs while connected for charging into the system. NFPA70 according to [62] focuses on the wiring and customer safety during the installment of EVs and other electrical equipment. The reports made on EVs and the related charging levels have revealed that the EVs have reached the number of 3 million and that number will increase in the upcoming years [63]. Canada has worked on the EVs field greatly as reported by Canadian Automobile Association (CAA).

The country has installed 7906 charging stations in its major cities and the number indicates the growth done in EVCS can be considered positive [12]. SAEJ2293 is responsible for making the required standards for the charging equipment. The standard is further classified into two sub-standards J2293-1 that include conductive AC, conductive DC, inductive charging, and J2293-2 that describes the architecture of EV charging equipment [64]. SAEJ1772 is the standard for equipment ratings for the EV charging that includes all the switch gears rating and more. SAEJ2931 standard is responsible for the software related queries that include the software requirements in the charging stations and other similar software's for charging of EVs and some precaution are also included there. Electrical vehicles are the need of time to get rid of pollution caused by old type of conventional transportation.

2.8 EVCS in Qatar

Moreover, Qatar General Electricity & Water Corporation (Kahramaa) launched recently EV charging stations guidelines for domestic and public utilization. As part of 2030 vision, a collaboration between Kahramaa and ministry of transport and communication (MOTC), Qatar adopts the electrification of transport section with main focus in first stage on public buses, school transportation as well as inside the compounds of Qatar Petroleum, Qatar Gas and other companies. For public EV charging station, the guidelines specify that rated power range of these EVCS is between 100kW to 150kW which classified as fast charging mode [13].

A lot of work has been done on the EVs and are going to be the future of upcoming generations The EV standard for Charging Station have also been focused so that EVs may not harm the system in which they get penetrated.

2.9 Contribution

Based on the conductive literature review in the field of EV-Grid interaction, there is a need to comparison studies of different EVCS and their impact on the local distribution network. The main focus previously was on evaluating of rectifiers and DC-DC converters performance for general applications. Recently, Kahramaa has several projects in participation with ministry of transport and communication (MOTC) and other entities to construct public fast charging EV charging stations as part of Qatar vision 2030. For that, several manufacturers, suppliers and contractors propose different types of EVCS to be installed into Kahramaa network as part of infrastructure services and hence it is highly important to evaluate the impact of these brands on the distribution before issuing the official approval. Moreover, this type of study will be proposed as part of Kahramaa EVCS guidelines in the future versions and if it is accepted, it will the first of its type and hopefully it will play crucial role in enhancement of utility services for EVCS.

2.10 Summary

Extensive literature review had been conducted in this chapter. Optimal placement and operation of EVCS through specific areas is one of the main fields that has been investigated thoroughly using optimization techniques to formulate and solve the problems. furthermore, other studies focused on EV charging impact on grid and EV load modelling using various mathematical tools and simulation software.

Because of the EV demand expansion, standards and governing regulations are developed to ensure safe and reliable operation the grid with EVCS integration.

Finally, thesis objectives, adopted methodology and thesis structure had discussed briefly.

Chapter 3: EVCS Design & Analysis

3.1 Introduction

In the fast charging mode that is used in most of the public charging stations require high power capability and for that, it is usually divided into two cascaded stages; AC-DC stage where the DC voltage is raised to higher levels that can reach up to 1200 V, and DC-DC stage in which voltage is bucked down to EV battery level. In general, EVCS consists of rectifier that will convert grid AC voltage to high voltage in range of 600 V to 1200 VDC and it will be bucked down to the level of battery level by DC-DC converter. Usually LC filter is installed between grid inlet and EVCS. Figure 3.1 shows the general arrangement of EVCS [11].

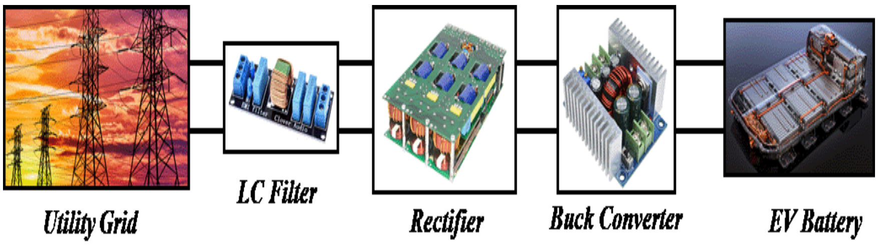

Figure 3.1. General topology of EVCS.

3.2 AC-DC Stage

The AC-DC stage plays crucial role in converting three phase AC into high DC voltage while keeping current sine wave THD at low level below standards. In this section, two types of AC-DC rectifiers have been simulated with input AC voltage of 415 V which is Kahramaa standard low voltage level. Grid frequency is 50 Hz and the output voltage of the rectifiers is 800DCV.

3.2.1 Vienna Rectifier

The first type of AC-DC rectifiers is Vienna rectifier which has been used widely in high power applications. The selected topology is shown in Figure 3.2 where there are three switching devices typically MOSFET or IGBT and each switch is surrounded by six diodes. In order to maintain the output voltage at the desired 800DCV level, PWM technique is applied and the results shown in Figure 3.3 where it can be shown that the signal experiences overshooting which kept below 1000 V and last for almost 0,01s before it reaches steady state with approximately clean DC voltage. The detailed steps of the control strategy are beyond the scope of this study and the interested reader can refer to [65] and [66] for more details on power converters control methods and techniques.

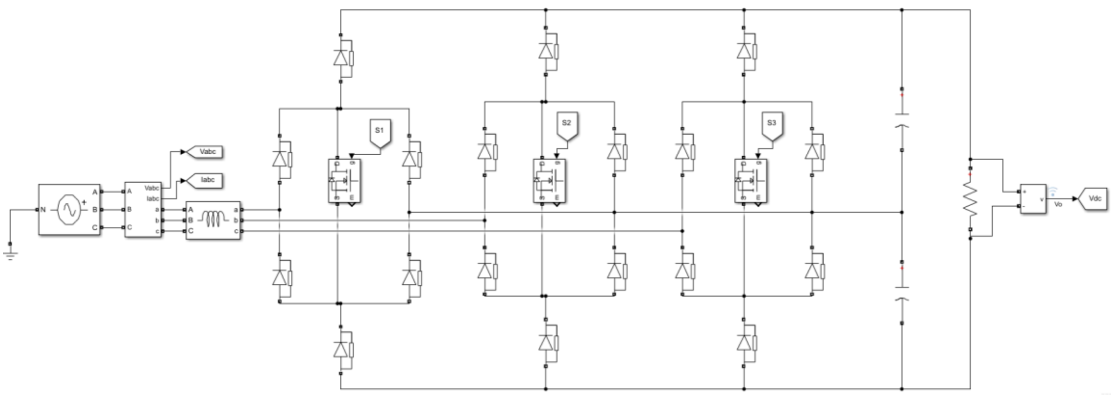

Figure 3.2. Vienna rectifier simulink model.

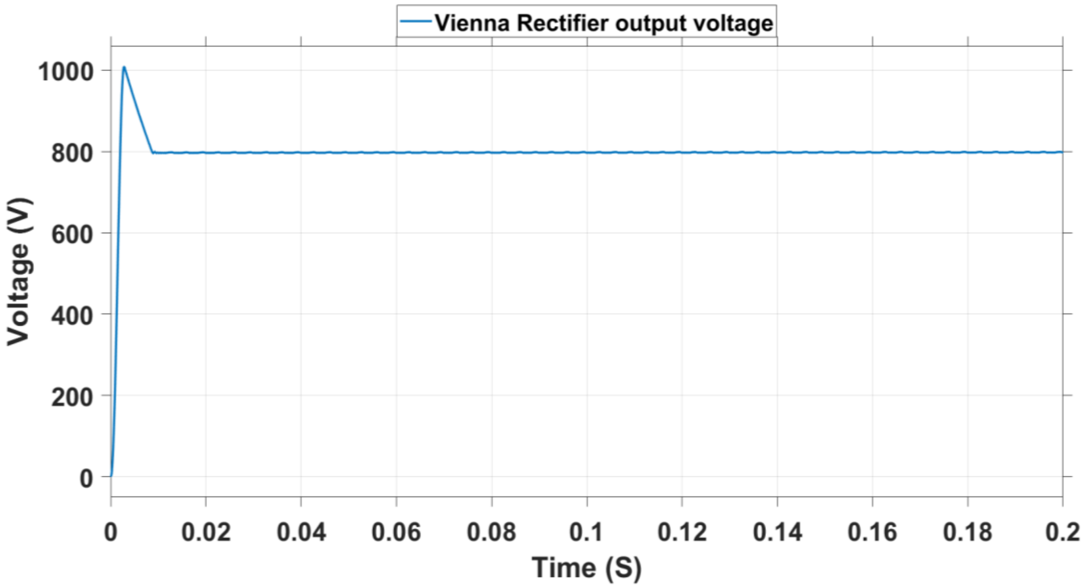

Figure 3.3. Vienna rectifier output voltage.

3.2.2 Front-End rectifier

This type of rectifiers has been considered as one of the robust and effective methods that minimize grid current THD level while having the ability supply power at high DV voltage levels. In Figure 3.4, the front-end rectifier is connected to three phase source through LCL filter and the output has been kept at 800 VDC which will be used as the input voltage at DC-DC stage. Figure 3.5 shows the topology of front-end rectifier where three legs with two switching devices are used. DQ-frame frame technique has been applied as a control scheme in order to control output voltage and the results shown in Figure 3.6 where the signal experiences overshooting that hit almost 1200V peak and the transient stage last for 0.1s when the signal reaches steady state values.

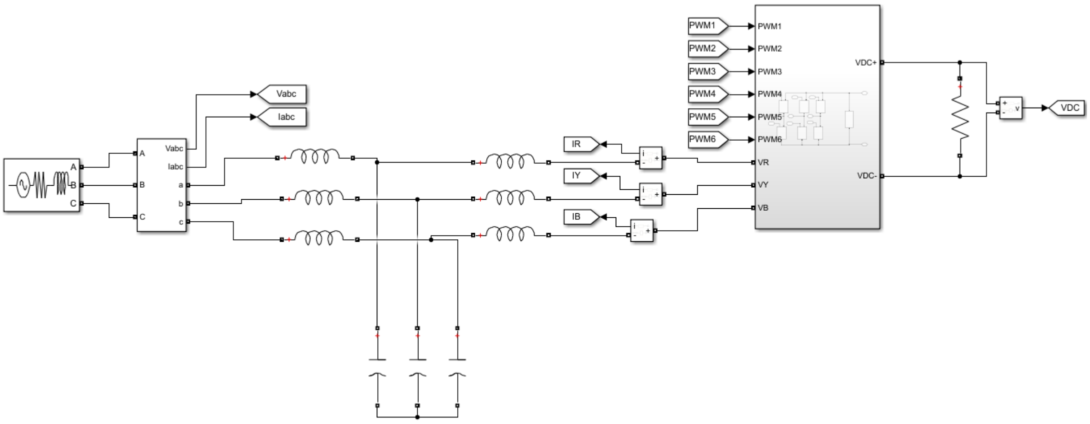

Figure 3.4. Front-end rectifier simulink model.

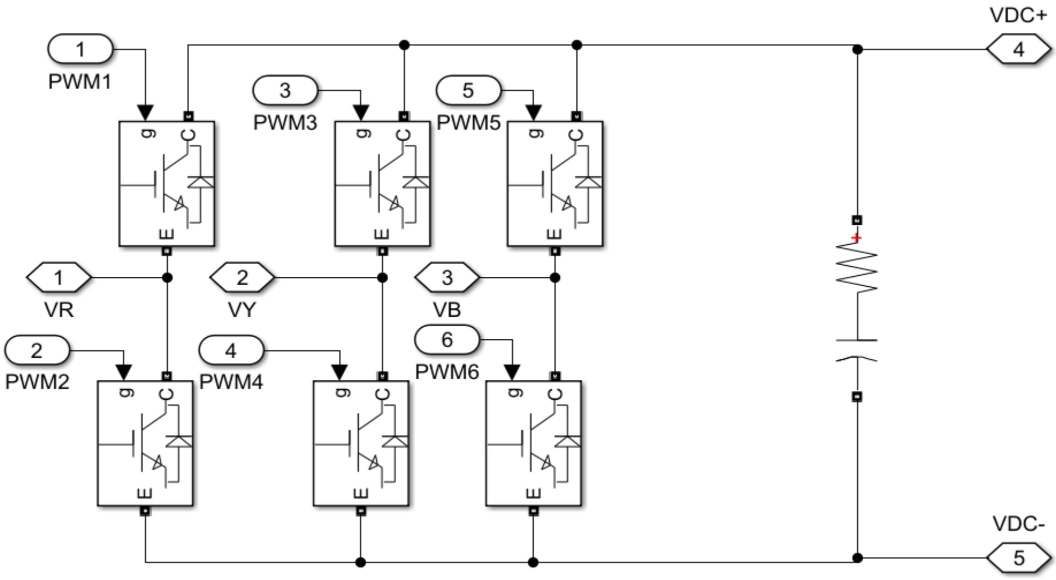

Figure 3.5. Front-end rectifier configuration.

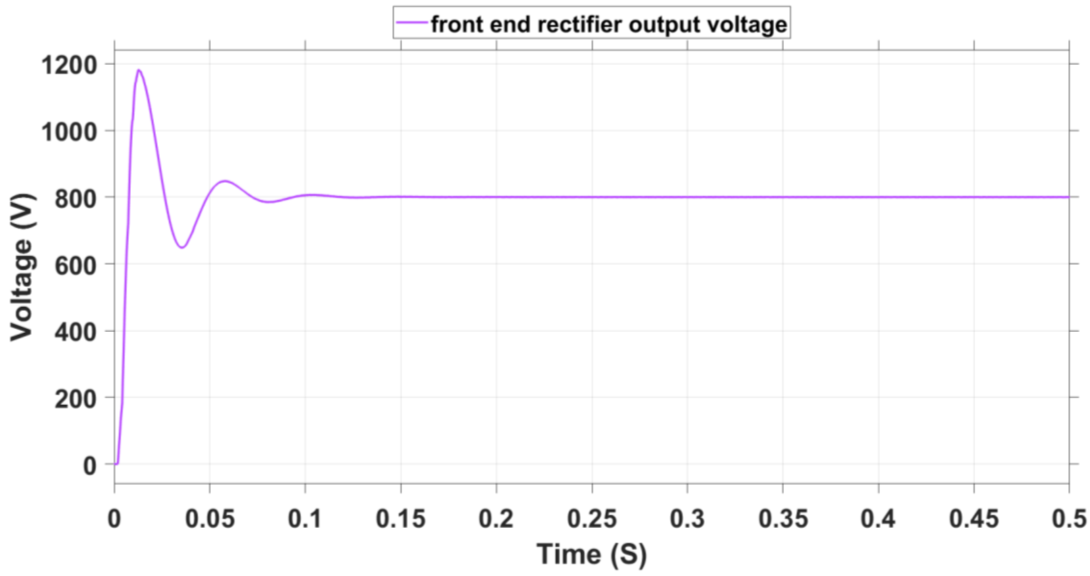

Figure 3.6. Front-end rectifier output voltage.

3.3 DC-DC Stage

The second stage of fast charging mode that is used in public EV charging station is DC-DC stage. In this stage, the high output voltage that has been achieved in the previous stage is bucked down to EV battery level. As per the applied standards, this stage shall serve wide range of voltages that can start with 50 V up to 400 V where it can supply the rated power to small load such as e-bike up to fast charging PHEV. In this section two types of DC-DC converters have been simulated with input voltage of 800 VDC and output of 400 VDC and 100 kW load is considered.

3.3.1 Dual Active Bridge (DAB)

First type of DC-DC converter is dual active bridge (DAB) converter where the topology is shown in Figure 3.7. It consists two parts separated by high frequency isolation transformer and each part has four switching devices that can be selected either MOSFET or IGBT. Due to the lagging nature of DAB because of primary side inductor, the current in the secondary discharged through the output capacitor.

Zero voltage switching techniques have been applied in this kind of topology in order to minimize conductive losses. Controlling phase angle between the two parts allows for bidirectional operation mode and this is considered as one of the main advantages which can be utilized in V2G mode.

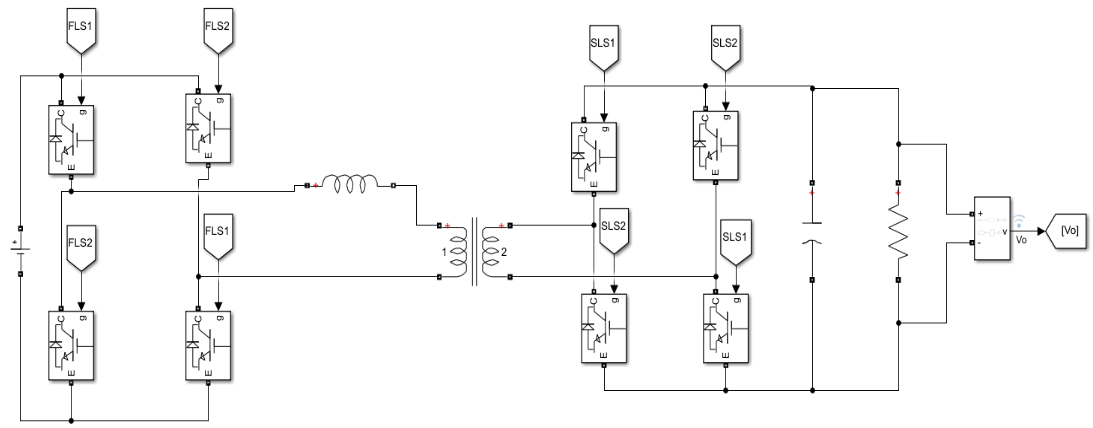

Figure 3.7. DAB converter simulink model.

In Figure 3.8, the output voltage and current waveforms are shown where the signals within time less than 0.01s reach the steady state of 400 V and 250 A respectively. The converter shows effective performance in the transient period where the overshooting percentage and settling time kept at very small values. In addition to that, the steady state error and ripple components were almost zero.

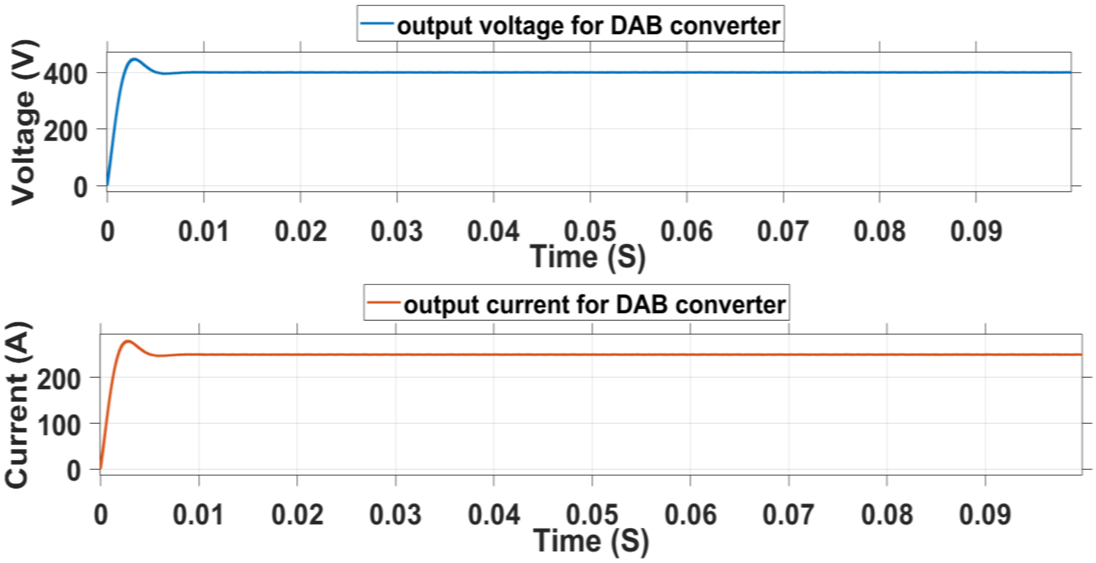

Figure 3.8. DAB output voltage & current.

3.3.2 Phase-Shifted Full Bridge (PSFB)

The second DC-DC converter that has been simulated in this chapter is phase-shifted full bridge converter where Simulink model in Figure 3.9 shows the topology of this type of converters. PSFB topology is similar to DAB converter in one way and differs in other aspects. It is similar to DAB in that it consists of two parts isolated by high frequency transformer. However, in PSFB second bridge, the switching devices replaced with diodes and the inductor is relocated in the output side rather than input as in the case of DAB. This topology uses variable phase shift method to control the amount of power transferred from the primary side to the secondary and because of the existence of passive diodes, PSFB experience non zero voltage switching which degrade the efficiency of the converter.

Figure 3.10 shows the output voltage and load current waveforms where it can be seen that the transient period last for very short time and steady state values are clean with approximately zero steady state error and ripples.

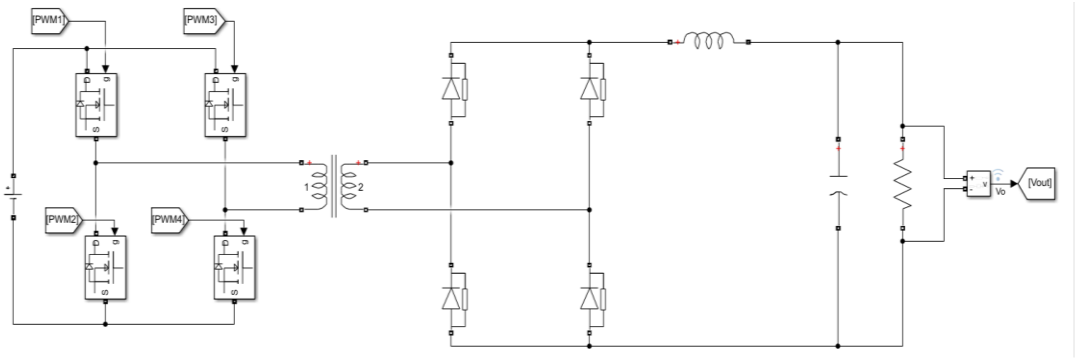

Figure 3.9. PSFB converter simulink model.

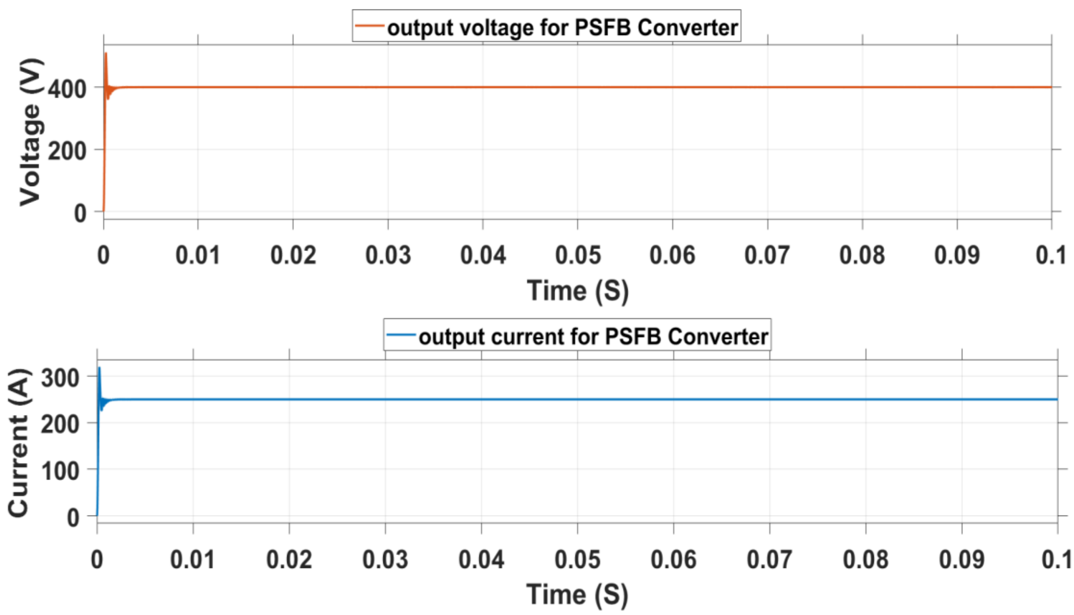

Figure 3.10. PSFB output voltage & current.

3.4 EVCS Type-1 Vienna Rectifier +DAB Converter

The first type of EV charging stations simulated is combination of Vienna rectifier along with DAB DC-DC converter as it shown in Figure 3.11. The system is connected to three phase 415 V, 50 Hz sources to resemble Kahramaa distribution voltage level and grid frequency respectively. The rectifier output voltage is shown in Figure 3.12 with steady state value of 800 VDC and the signal suffers ripples and long settling time response of 0.02s though overshooting is relatively small.

Moreover, EVCS output voltage and load current results shown in Figure 3.13 where 400 V and 250 A steady state values can be seen. The transient period lasts for approximately 0.01s and the overshooting spike above 600 V though it remains for short period only.

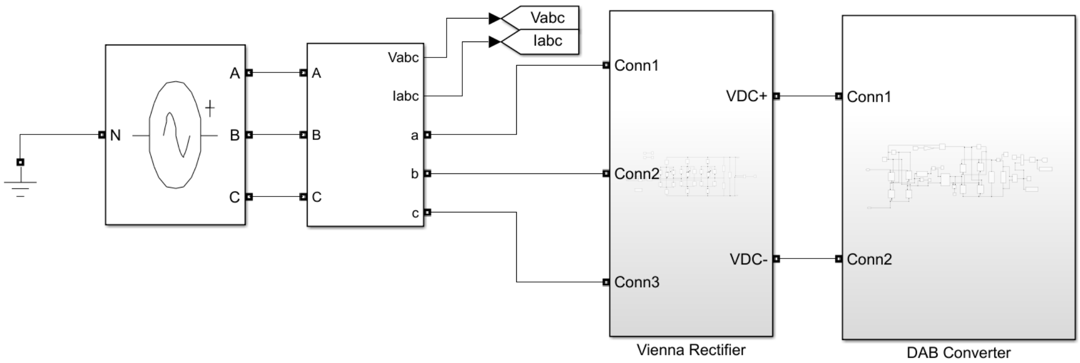

Figure 3.11. EVCS type-1 simulink model.

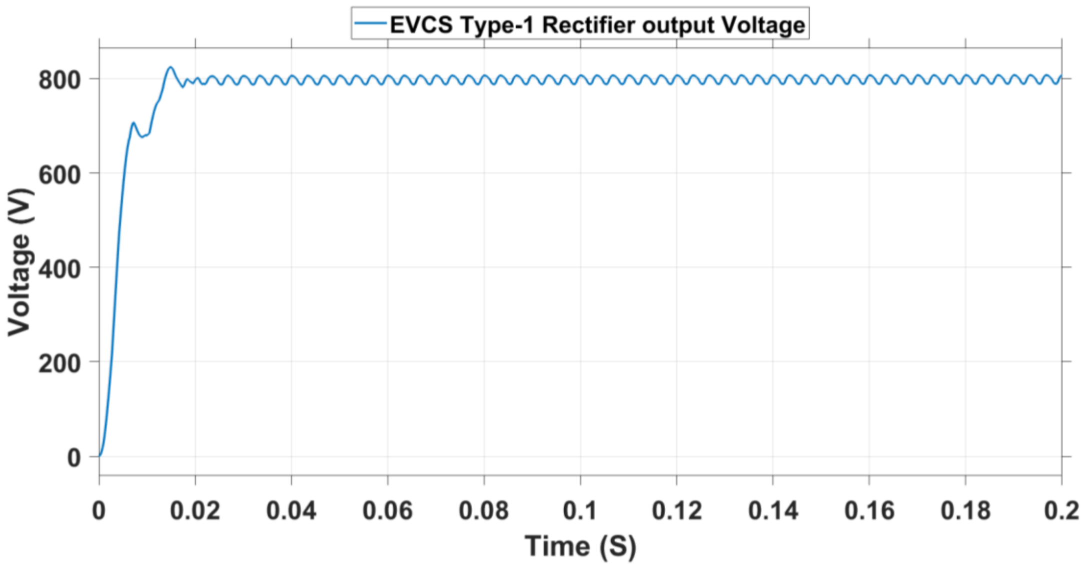

Figure 3.12. EVCS type-1 rectifier output voltage.

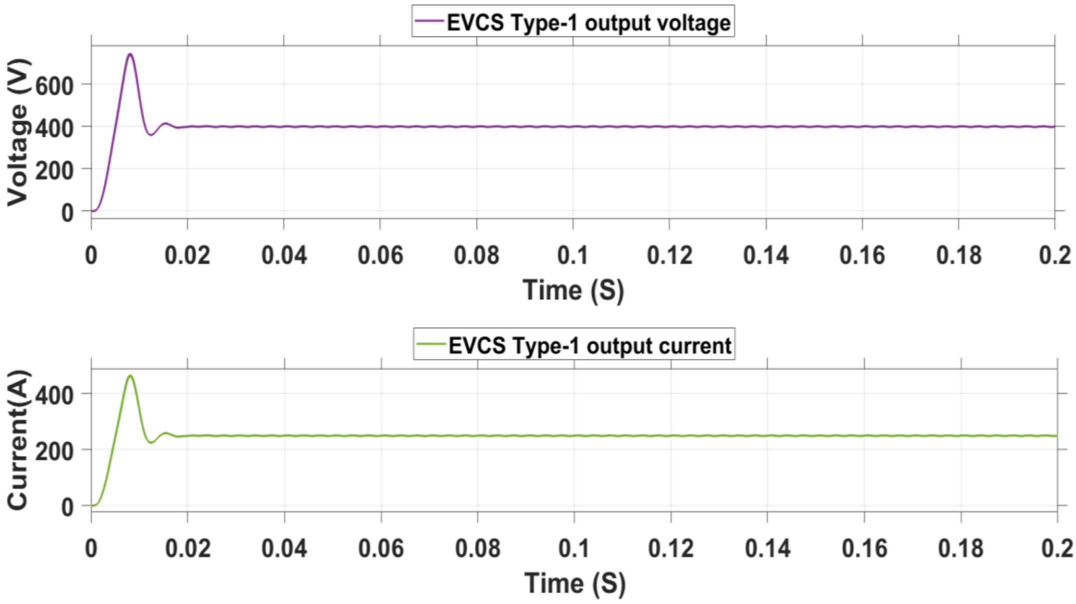

Figure 3.13. EVCS type-1 output voltage & current.

EVCS Type-1 performance varies in comparison to the performance of standalone operation of the converters. For instance, rectifier output voltage ripples rise in EVCS while it reaches almost zero value before the Vienna rectifier is connected to DAB converter. However, type-1 combination shows better performance in in terms of transient overshooting value when it is compared to the performance of the rectifier. On the other hand, the performance of DC-DC stage in EVCS type-1 is relatively similar to the performance of the DAB converter in the steady state period even though the EVCS combination experiences higher overshooting.

3.5 EVCS Type-2: Vienna Rectifier +PSFB Converter

In EVCS type-2 combination, DAB is replaced with phase-shifted full bridge converter (PSFB) as it shown in Figure 3.14. Though the rectifier used in the previous type was the same, it can be seen from the results that the overall performance differs from type-1 combination in both transient and steady state periods. AC-DC stage Output voltage is shown in Figure 3.15 where it shows smooth steady state and zero overshooting. Moreover, EVCS type-2 output voltage and load current hit the expected values of 400 V and 250 A respectively with less than 0.01s as it demonstrated in Figure 3.16.

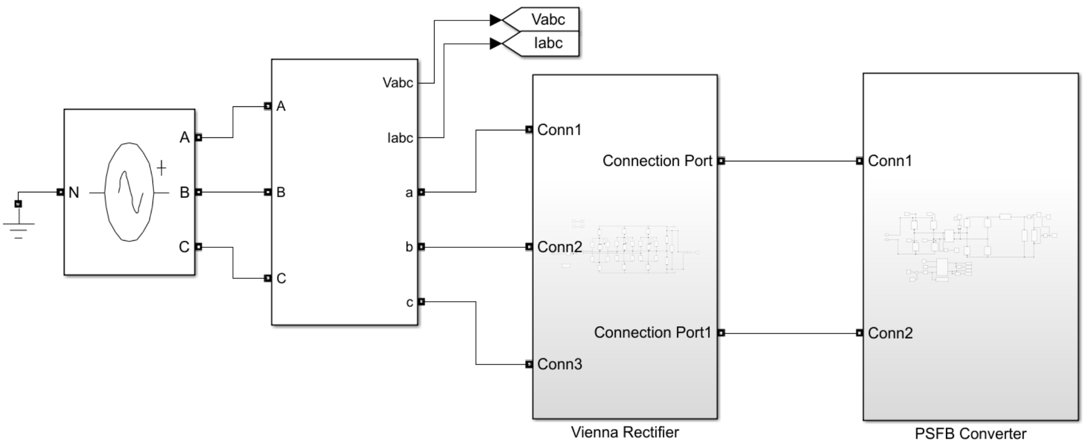

Figure 3.14. EVCS type-2 simulink model.

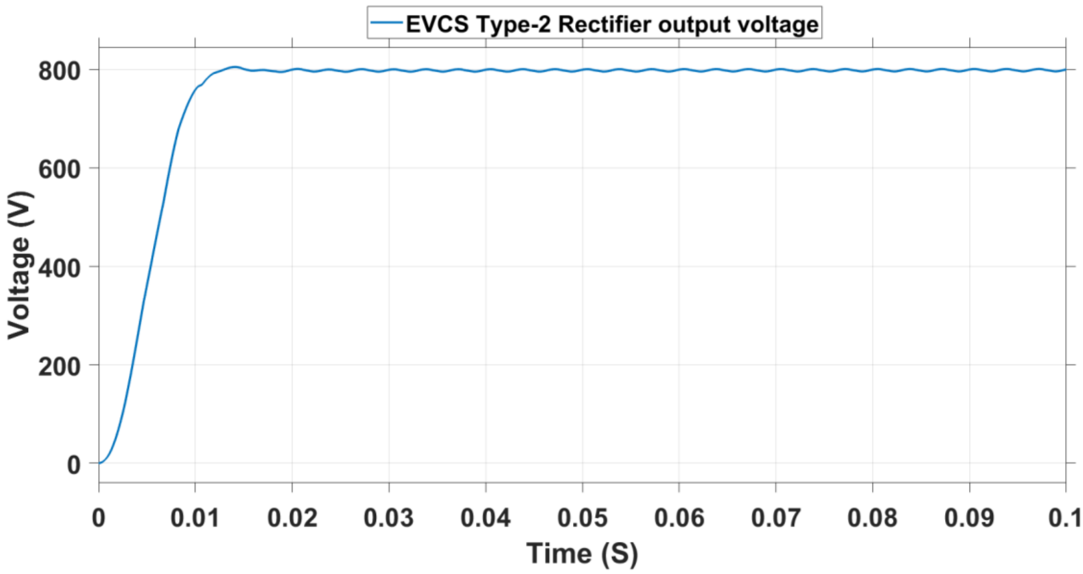

Figure 3.15. EVCS type-2 rectifier output voltage.

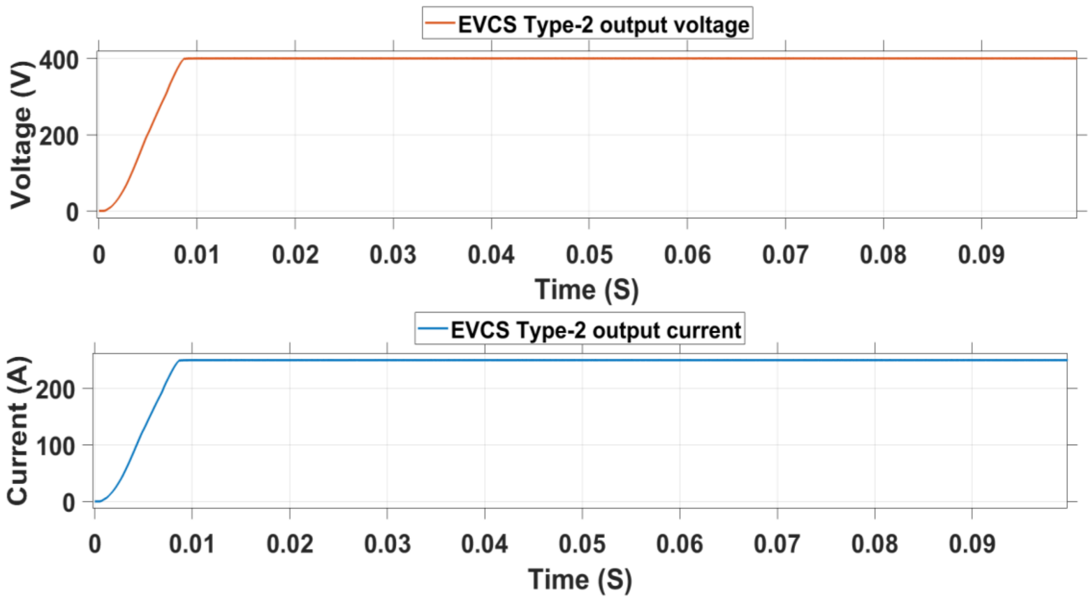

Figure 3.16. EVCS type-2 output voltage & current.

In this combination, Vienna rectifier show good performance compared the performance of standalone operation and it can be seen smoothing transition from transient period to steady state with zero overshooting. In addition, PSFB converter experiences instantaneous high overshooting while output voltage of DC-DC stage in EVCS type-2 shows smooth transient period with settling time less than 0.01.

3.6 EVCS Type-3 Front-End Rectifier +PSFB Converter

In the third combination, PSFB is connected to the front-end rectifier Simulink block diagram shown in Figure 3.17 and as in the previous combinations, the system is connected to three phase 415V and 50Hz in order to investigate the performance of this combination in contrast with the performance of standalone operation of front-end rectifier as well as PSFB. EVCS type-3 rectifier output voltage is shown in Figure 3.18 where the waveform transient period lasts for long time of 0.05s and overshooting peak arise beyond 1200 V which considered risky specially when the settling time is long. However, EVCS output voltage and load current performed well in this combination with smooth steady state value and almost zero ripples as it is shown in Figure 3.19.

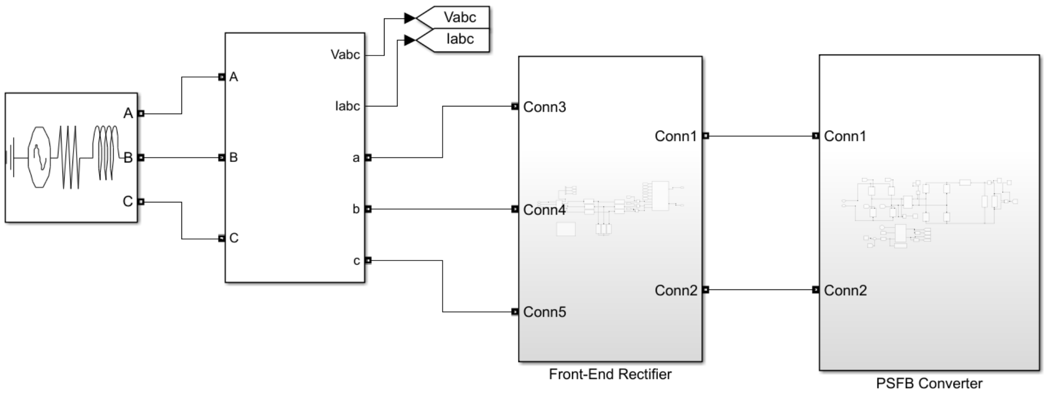

Figure 3.17. EVCS type-3 simulink model.

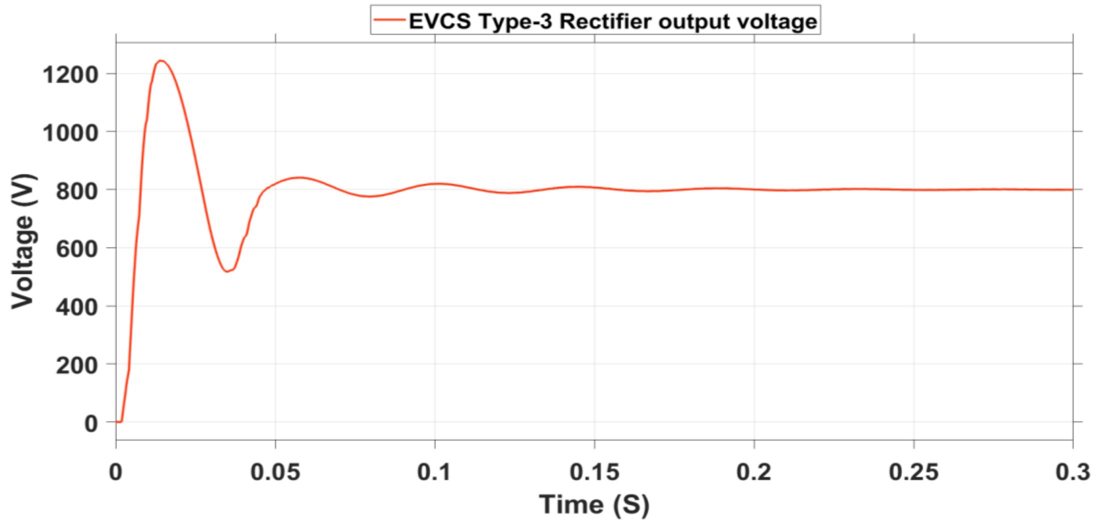

Figure 3.18. EVCS type-3 rectifier output voltage.

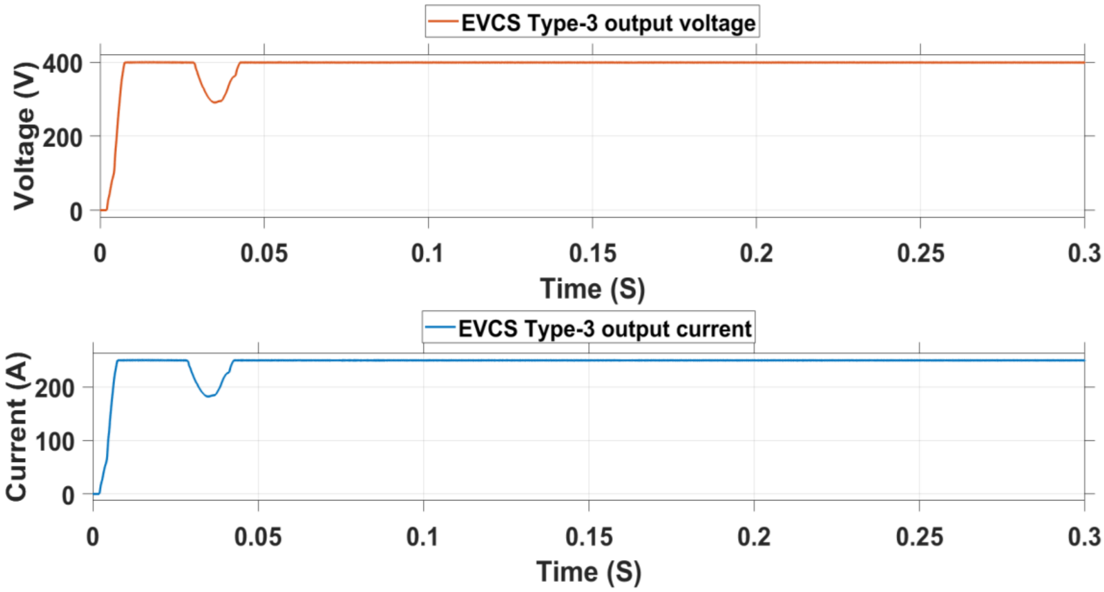

Figure 3.19. EVCS type-3 output voltage & current.

One of the observations that have been noticed in the results is the v-shaped drop in voltage and current waveforms during transient period and if it is compared to the rectifier output voltage, it occurred in when the output voltage drops below the rated value of 800 V. this observation indicates that the control is robust for voltage rise but very sensitive to high drop and can be seen that voltage wen below 600 V in that time window.

3.7 Summary

In this chapter, two types of rectifiers and DC-DC converters have been simulated for fast charging requirements. Out of these rectifiers and converters, three EVCSs combinations are simulated using MATLAB/SIMULINK software with 800 V rectifier output voltage, 400 V DC-DC converter output voltage and 250 A load. The results have been investigated in terms of transient overshooting, settling time as well as steady state error in order to evaluate the integration visibility into grid.

In the next chapter, the three types will be integrated into distribution network resembling branch of Kahramaa residential and commercial areas. System Performance evaluation for each type is investigated in terms of THD level, voltage drop and power losses at specific targeted buses

Chapter 4: Impact of Several EVCS Types Penetration on Distribution System Performance

4.1 Introduction

In the beginning of this chapter, modelling and simulation of 15-bus distribution network resembling Kahramaa. This distribution power system consists of 14 load centers that have been supplied from the main primary substation through 11kV feeders. Single line diagram is sown in Figure 4.1. The EVCSs that had been simulated in the previous chapter have been integrated into the distribution system and several scenarios are investigated for THD level, voltage drop and power losses. Lastly, performance of the distribution system in the presence of different EVCSs is compared.

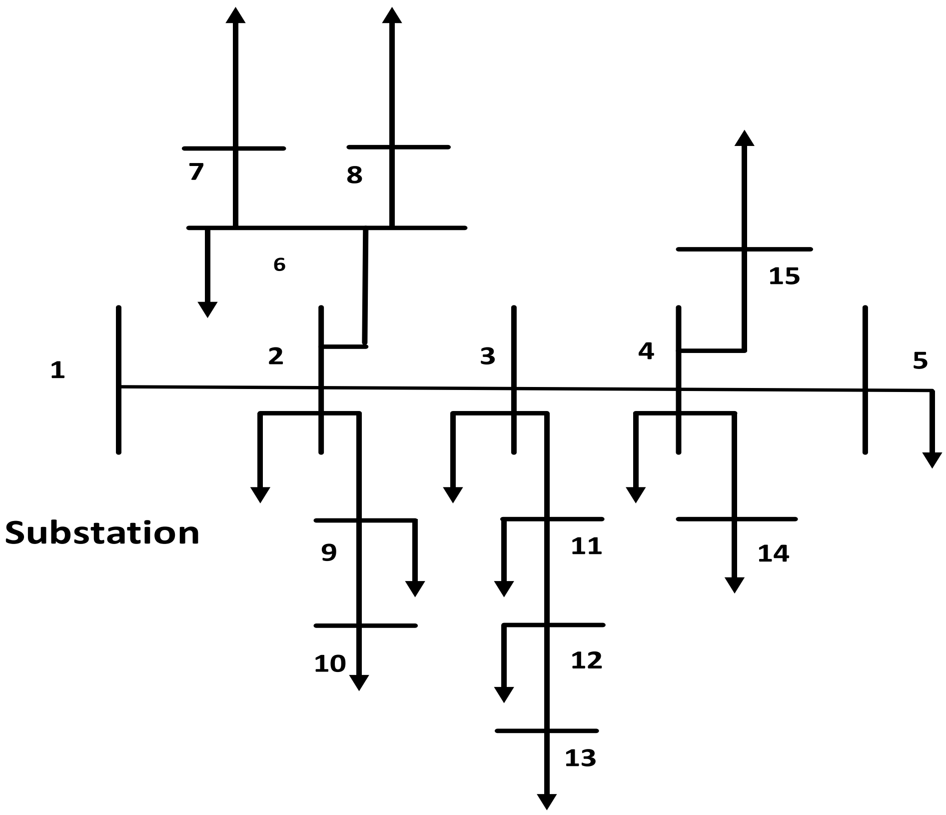

Figure 4.1. Distribution network single line diagram.

4.2 Modelling and simulation of 11kV distribution network

The system as it is shown in Figure 4.2 is 11kV 15-bus system and the main primary substation is rated of 40 MVA which is considered as one of the standard values applied in accordance with Kahramaa rules and regulations. Bus 3 and buss 6 are the most loaded buses in the system and the load range varies from 144 kW up to 1200 kW as the allowable limit of the standard 1600 kVA transformer. Five buses have been selected for the EVCS connections, namely; bus 5,6,10,12 and 15. The loaded buses and buses that are located in far areas are used as the main criteria of the selection process in order to investigate the worst case scenarios.

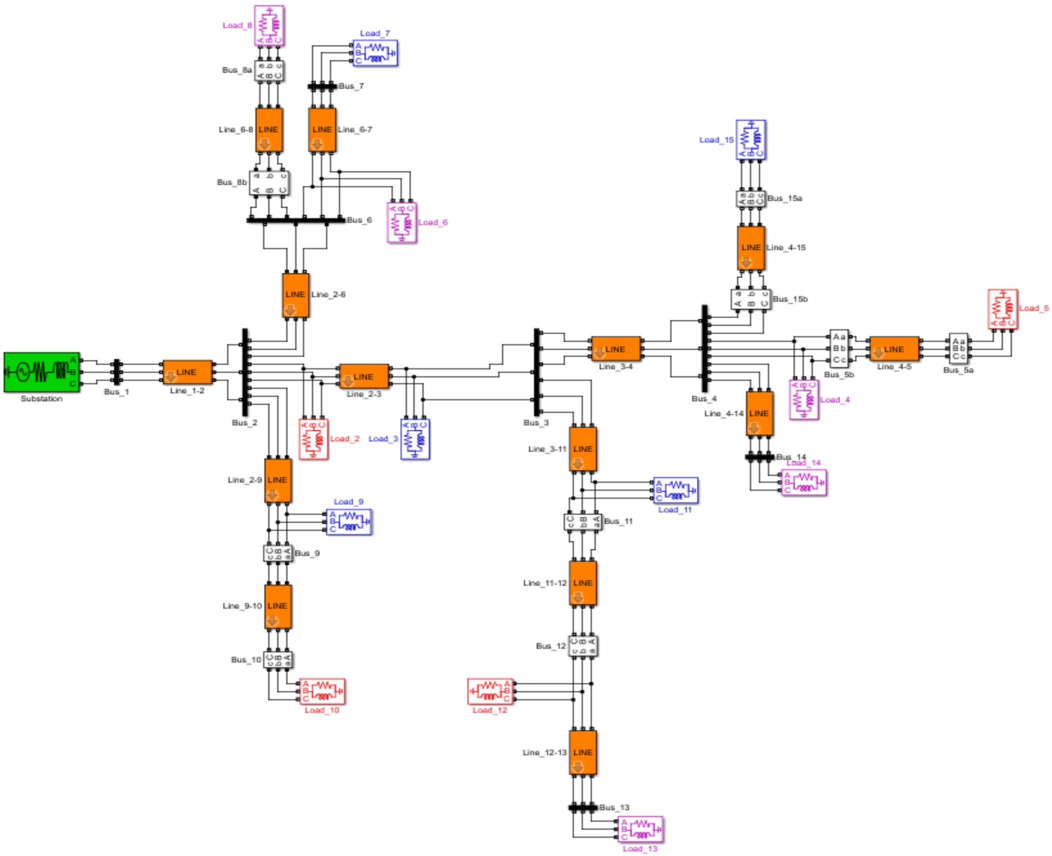

Figure 4.2. Simulink model for Kahramaa distribution network branch.

Line losses of the selected buses summarized in table 4.1 and these values will form the base for comparison of different types of EV charging stations and performance evaluation of the distribution network.

Line 11-12 shows the maximum loss among the selected buses with line losses value of 1.196kW and line 4-5 gives the smallest value of 0.04381kW.

Table 4.1. Line & Total Losses for The Key Model

Line No.	Line Losses (kW)
4-5	0.04381
4-15	0.08594
11-12	1.19600
9-10	0.04950
6-8	0.36280
Total Losses	55.4580

Moreover, the second parameter that will be investigated is voltage drop at the chosen buses and the local voltage drop regulations imposed by Kahramaa as it is detailed in table 4.2 formulates the evaluation criteria for the performance of EV charging stations. Kahramaa stated 6% allowable drop from the nominal value of 415 V RMS and in terms of peak value, the LV bus voltage shall not drop below 551.68 V in order for the design to be approved by local power provider. For the total harmonic distortion as the third parameter that will be evaluated, the 5% IEEE standard limit is used for the evaluation of EVCSs penetration levels [67].

Table 4.2. Kahramaa Voltage Drop Standards

Parameter	Value
KM Line voltage (RMS)	415V
KM Line voltage (Peak Value)	586.9
Standard limit	6%
Allowable voltage drop	24.9V
Minimum limit (RMS)	390.1V
Minimum limit (Peak value)	551.68V

4.3 Impact of Type-1 Charging Station

The first type of EVCS that consists of Vienna rectifier combined with DC-DC dual active bridge converter is connected into the system at the targeted buses (5, 6, 10, 12 and 15) as it shown in Figure 4.3. The evaluation of the charging station has been studied in the previous chapter and the input DC voltage, output voltage as well as load current have been verified to meet the desired requirements. However, the EVCS previous results were conducted in standalone single source mode and they need to be tested again once the EV charging stations are integrated into the system. The input DC voltage and the output voltage and current of grid-connected EVCSs of type-1 are shown in Figure 4.4 and Figure 4.5 respectively.

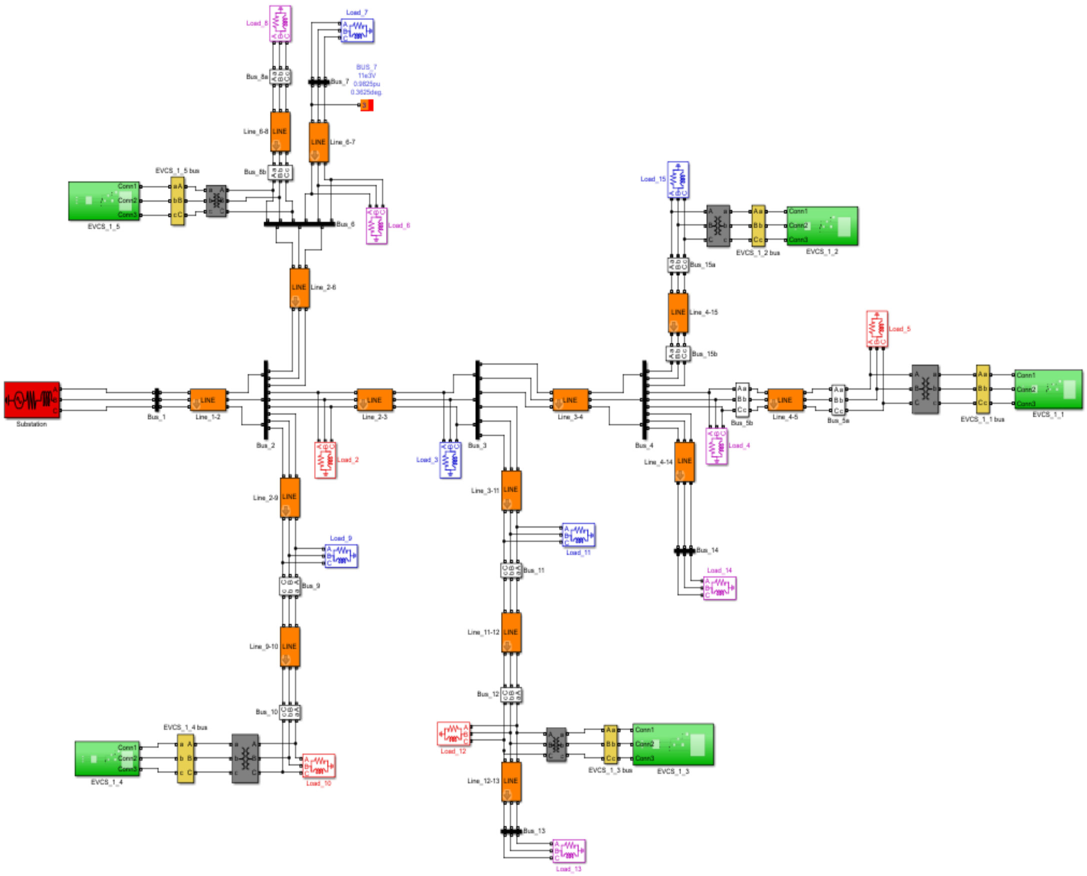

Figure 4.3. EVCS-connected distribution network (type-1).

The rectifier output voltage shows ripples in the steady state and that may cause fluctuation in the EVCS output voltage. On the other hand, the signal experiences sharp drop in the transient period where the voltage drops extensively below 600 V. the settling time of the signal is almost 0.04s which considered slower than standalone value of 0.02 and this degradation in performance effects the selection of protection devices. However, looking at output DC voltage and load current in Figure 4.5, it is performing good in steady state time with very small steady state error though the signal in the transient period exceeds 600 V and 400 A for load voltage and current respectively. In comparison to rectifier output voltage transient response, the settling time of EVCS output voltage is approximately 0.02s and this value relatively close to the standalone performance.

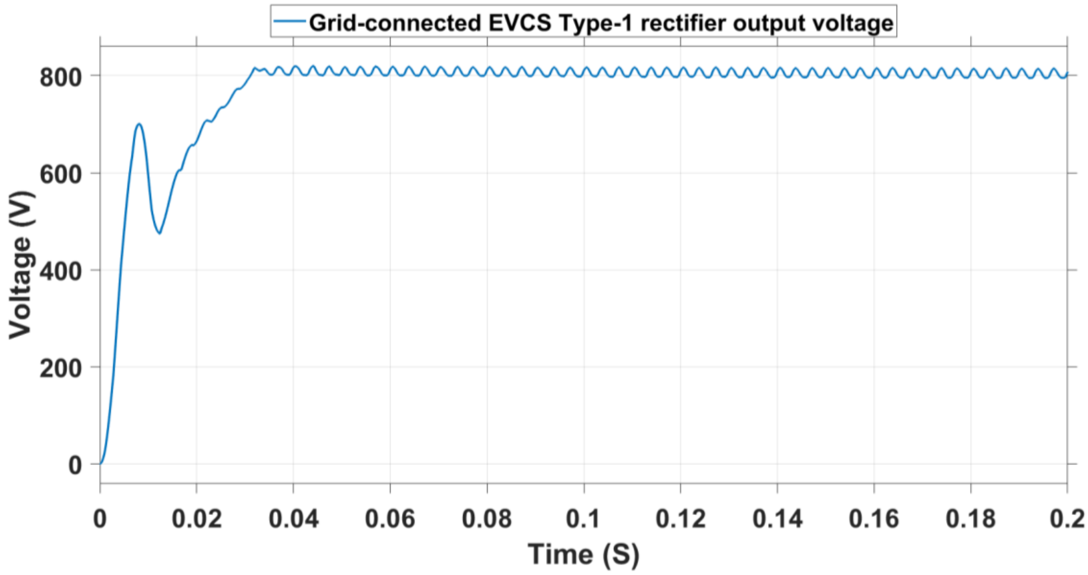

Figure 4.4. Grid-connected EVCS rectifier output voltage (type-1).

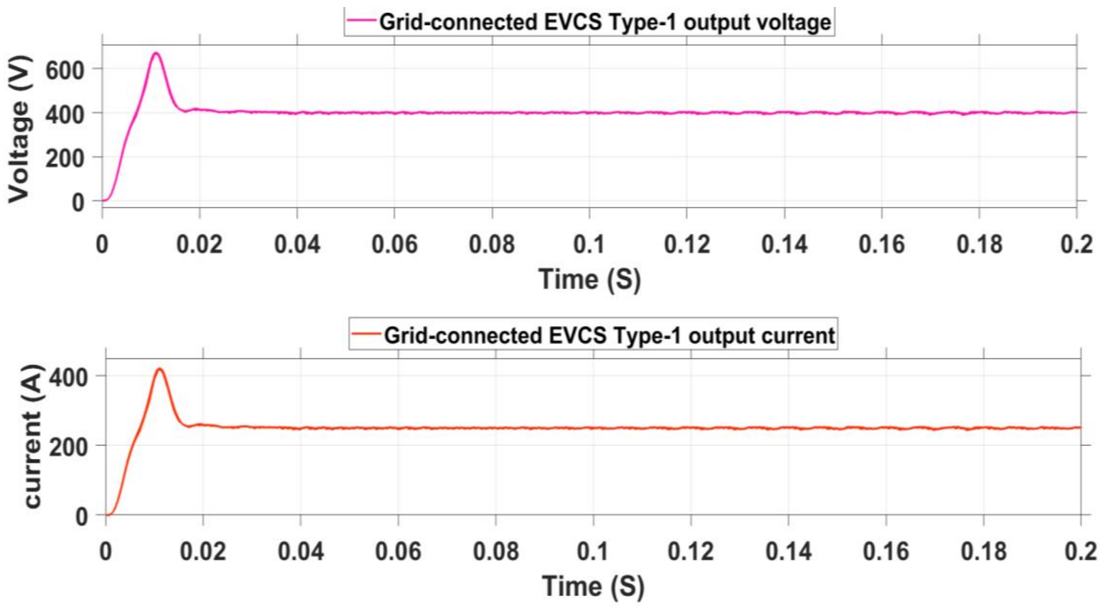

Figure 4.5. Grid-connected EVCS output voltage & current (type-1).

After studying the performance of EVCS when is connected the system, it is time to look at system performance in terms of THD, voltage drop and losses parameters.

4.3.1 Impact on THD

The total harmonic distortion results at the selected buses are shown in Figure 4.6 up to Figure 4.10 where five EVCS of type-1 is connected to the system as shown previously in Figure 4.3. In Figure 4.6 and Figure 4.8, THD level hit maximum value of 3.68% in comparison to others indicating that bus 5 and bus 12 have less margin in terms of THD level when they compare to the other buses. Buses 15 and 10 have 3.66% and 3.44% THD values respectively as it shown in Figure 4.7 and Figure 4.9. the least value is found at bus 6 where the value of THD is 3.35 as in Figure 4.10 indicating that this bus is most optimal place where more EVCSs can be integrated.

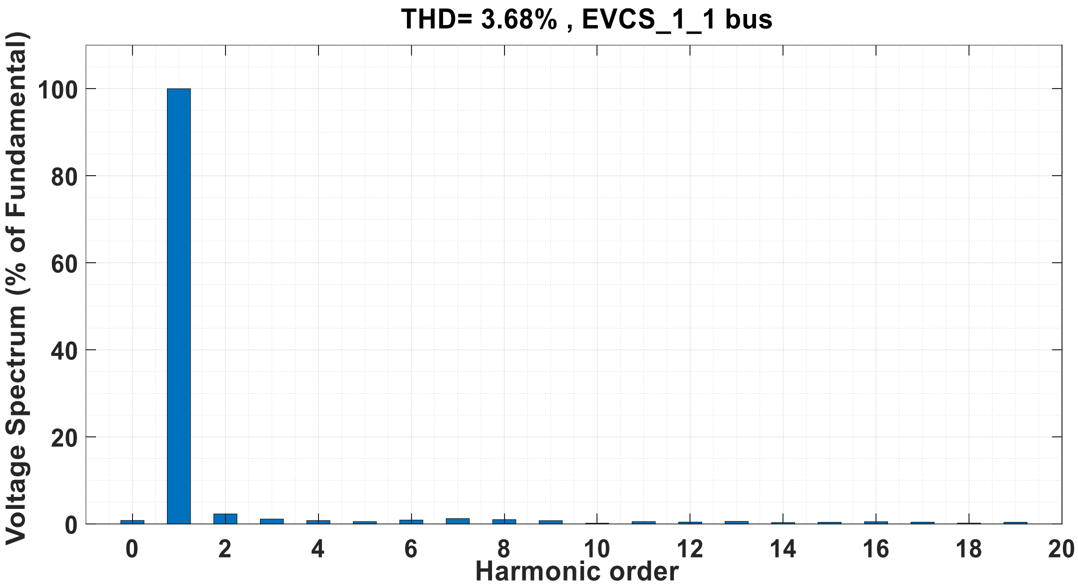

Figure 4.6. THD level at EVCS_1_1 bus (type-1).

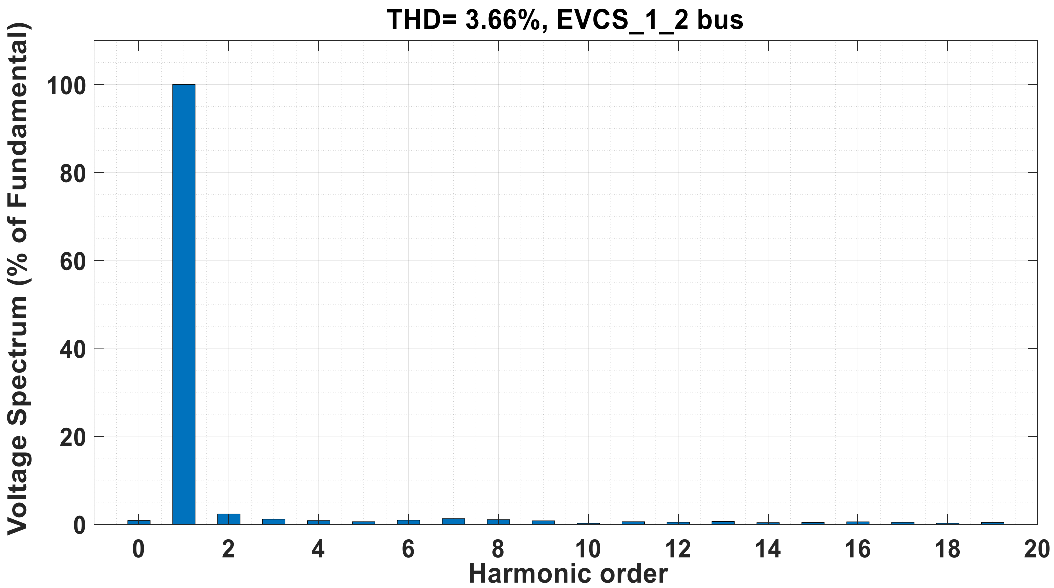

Figure 4.7. THD level at EVCS_1_2 bus (type-1).

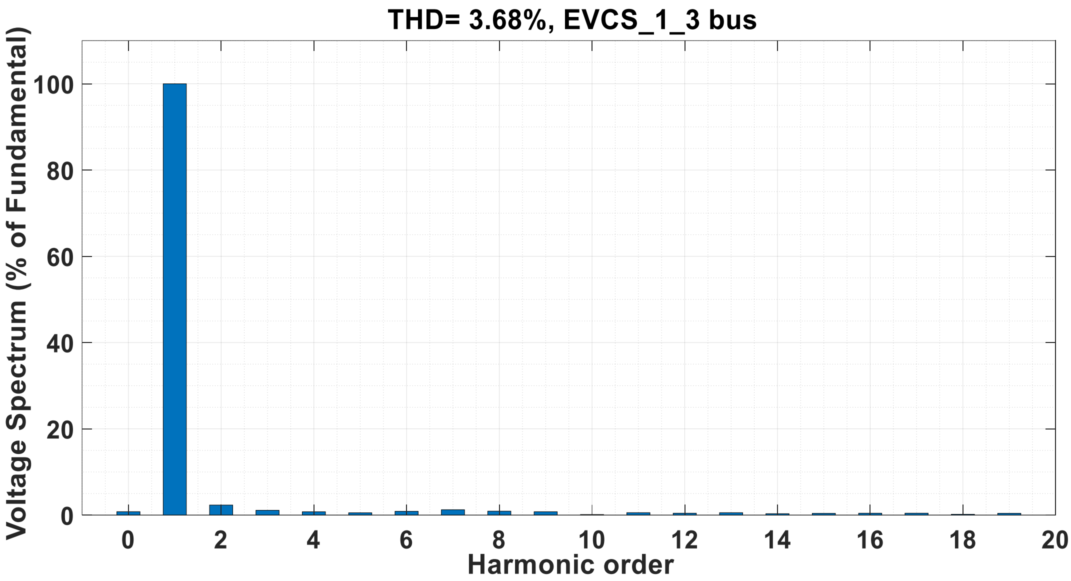

Figure 4.8. THD level at EVCS_1_3 bus (type-1).

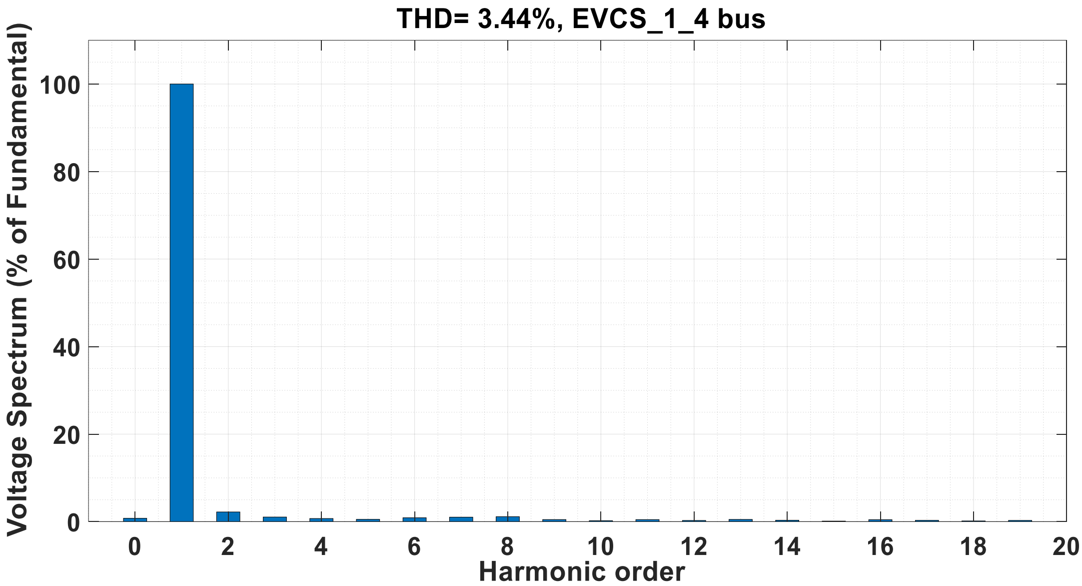

Figure 4.9. THD level at EVCS_1_4 bus (type-1).

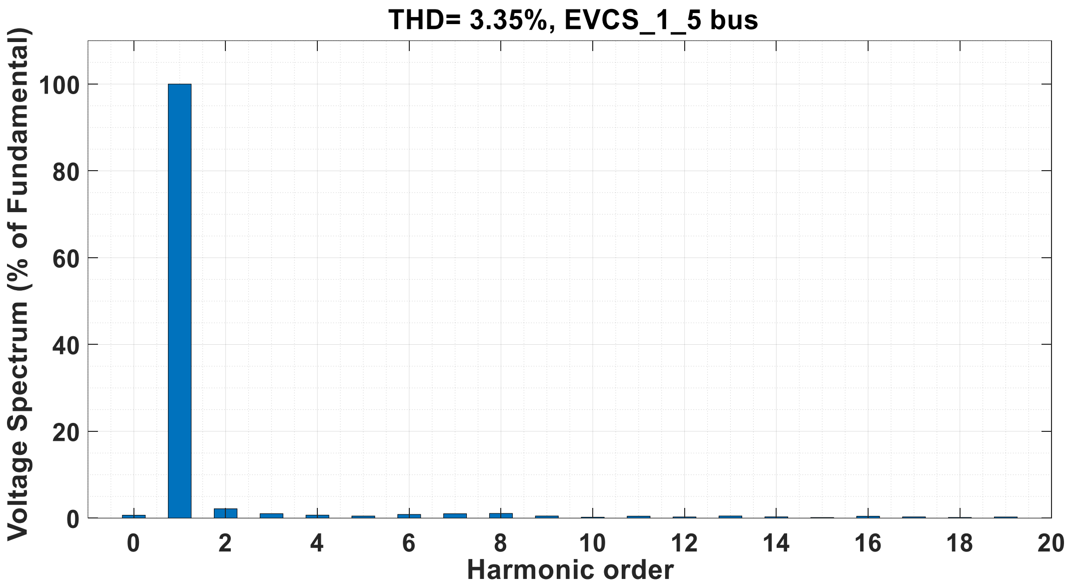

Figure 4.10. THD level at EVCS_1_5 bus (type-1).

Although, there slight variation in THD values of the selected buses when they connected to type-1 EV charging stations, they are all in range of 3%-4% where it gives average margin of 1.5% for EVCS load increases before the bus THD hit the 5% standard value. Summary of EVCS type-1 THD values is given in table 4.3.

Table 4.3. THD Level Summary (EVCS Type-1)

Bus No	THD (%)
EVCS_1_1	3.68
EVCS_1_2	3.66
EVCS_1_3	3.68
EVCS_1_4	3.44
EVCS_1_5	3.35

4.3.2 Impact on Voltage drop

The second system performance evaluation parameter is voltage drop at EVCS-connected buses. Figure 4.11 to Figure 4.15 show the results of low voltage waveforms at the targeted buses. The values range from 557.4V up to 569.2V which is below the nominal value of 586.9V and above the lowest allowable limit of 551.68V as per Kahramaa standard. The maximum voltage drop occurred at bus 12 as in Figure 4.13 while the minimum drop took place at bus 10 where the result is shown in Figure 4.14. buses 5, 15 and 6 showed values of 561.9V,560.3V and 562V respectively as shown in Figure 4.11, 4.12 and 4.15.

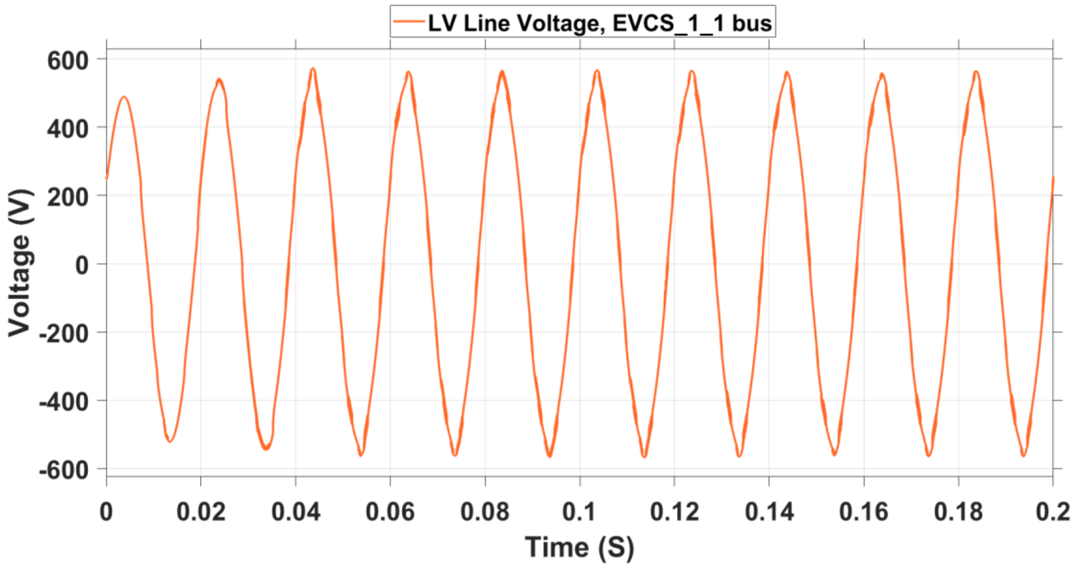

Figure 4.11. LV line voltage at evcs_1_1 bus (type-1).

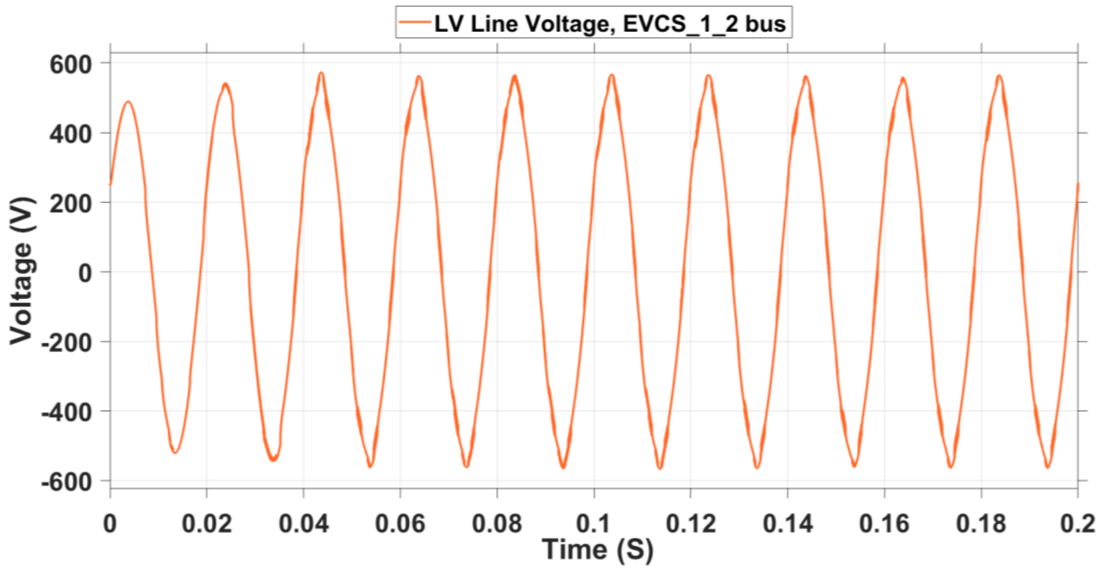

Figure 4.12. LV line voltage at evcs_1_2 bus (type-1).

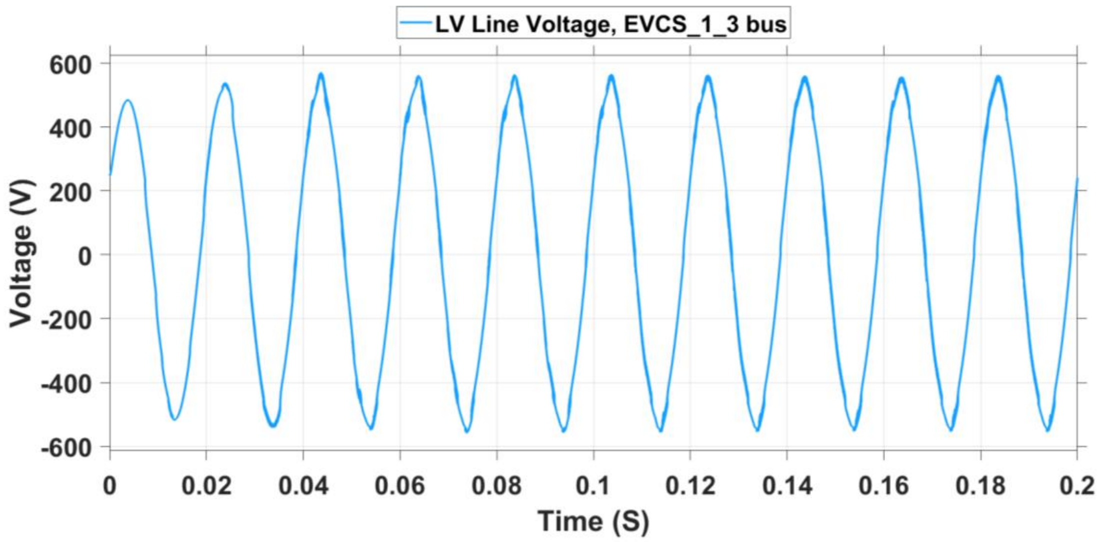

Figure 4.13. LV line voltage at evcs_1_3 bus (type-1).

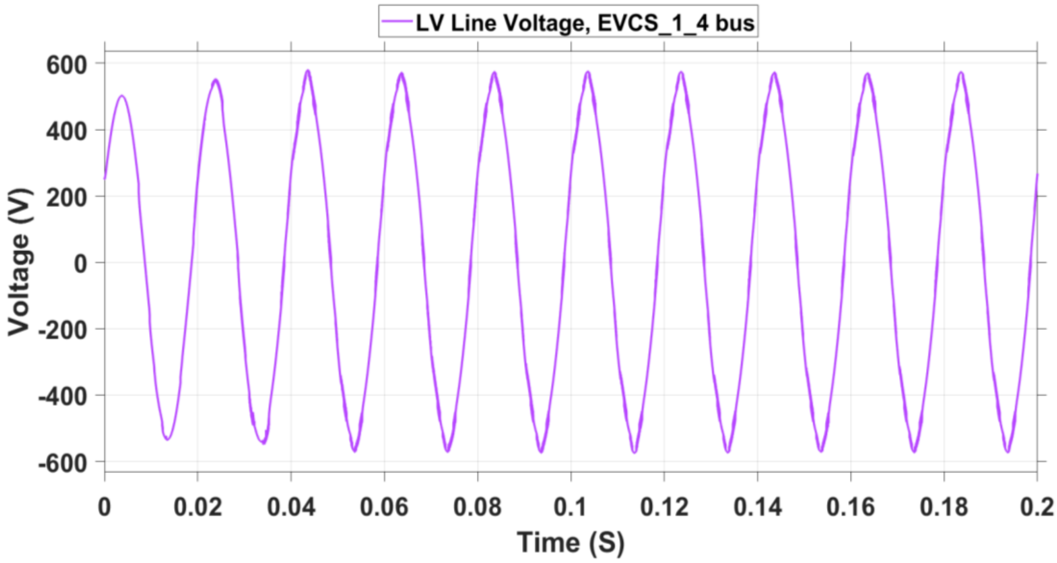

Figure 4.14. LV line voltage at evcs_1_4 bus (type-1).

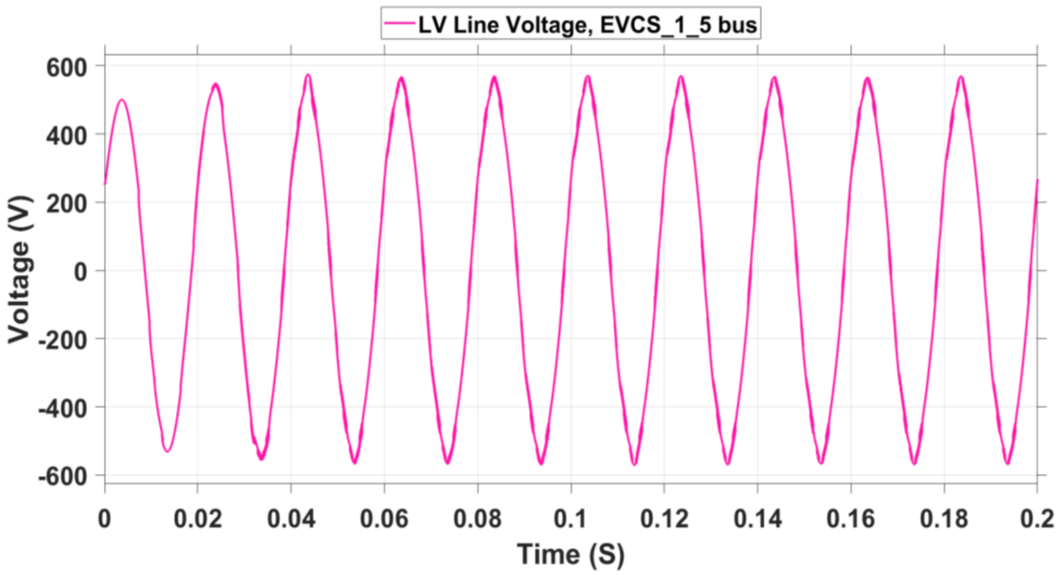

Figure 4.15. LV line voltage at evcs_1_5 bus (type-1).

The voltage waveforms show good performance in both transient and steady state periods with almost zero ripples and that gives an indication that the system perform well with EVCS type-1 penetration. Table 4.4 provide summary of line voltage peak values at the targeted buses. None of the buses violated the standard limit of 6% imposed by Kahramaa. Hence, the design is considered acceptable in terms of voltage drop criteria.

However, in some cases, Kahramaa impose 4% instead of 6% in the remote areas or the areas where the existing load is not recorded. In that case, installation of EVCSs is not recommended due to tight tolerance voltage limits.

Table 4.4. Line Voltage Peak Values (EVCS Type-1)

Bus No	Line Voltage (V)
EVCS_1_1	561.9
EVCS_1_2	560.3
EVCS_1_3	557.4
EVCS_1_4	569.2
EVCS_1_5	562

4.3.3 Impact on Line and Total Losses

The third parameter that has been investigated is line and total losses. The summary of line losses in EVCS type-1 is given in table 4.5 where the resulted losses are compared with the key model losses and system total losses. Tdhe line that connects buses 6 to 8 experiences the least line losses increase of 0.0115kW with 0.02% of the total losses. On the other hand, bus 11-12 resulted increase of 0.938kW as the maximum value among all EVCS-connected buses and it is 1.69% of system total losses.

Table 4.5. Line & Total Losses Results (EVCS Type-1)

EVCS_1 Line No.	Line Losses (kW)	Losses increase (kW)	Percentage of Total Losses (%)
4-5	0.3738	0.32999	0.60
4-15	0.4778	0.39186	0.71
11-12	2.134	0.938	1.69
9-10	0.2111	0.1616	0.29
6-8	0.3743	0.0115	0.02
Total Losses	56.812	1.354	2.44

The main causes of this variation in line losses is line impedance, bus connected load as well as the absorbed reactive power. Part from THD and voltage drop, the line losses can increase power cost and for that Kahramaa imposed strict regulations to be implemented in order to mitigate the impact of power losses and these regulations include installation of capacitor bank at load side to supply the required reactive power. Moreover, in the remote areas where the existing distribution line is lengthy, Kahramaa recommends to install alternative power sources such as solar panel or wind turbine to supply part of the load and hence, release some the burden of public grid.

4.4 Impact of Type-2 Charging Station

The second type of EV charging stations that will be investigated is a combination of Vienna rectifier and phase-shifted full bridge (PSFB) DC-DC converter as it shown in Figure 4.16. Five numbers have been integrated into the distribution system at buses 5,6,10,12 and 15 as in the previous type. Firstly, the result of rectifier output is shown in Figure 4.17 where the signal has smooth steady state response in comparison with EVCS Type-1. The transient period settling time is approximately 0.04s and the waveform have not experienced any overshooting. Moreover, Figure 4.18 shows the results of EVCS output voltage and current and it can be seen that the desired steady state value was achieved in less than 0.02s with almost zero ripples.

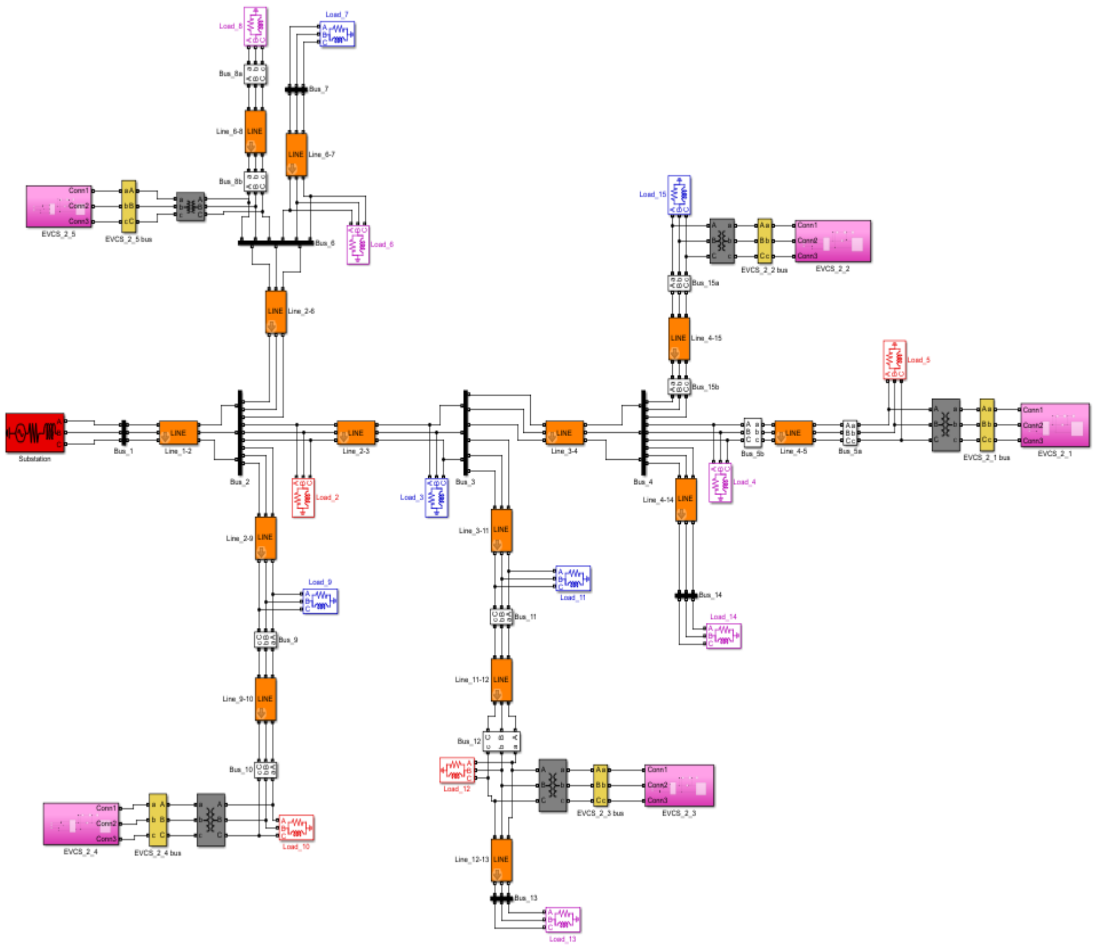

Figure 4.16. EVCS-connected distribution network (type-2).

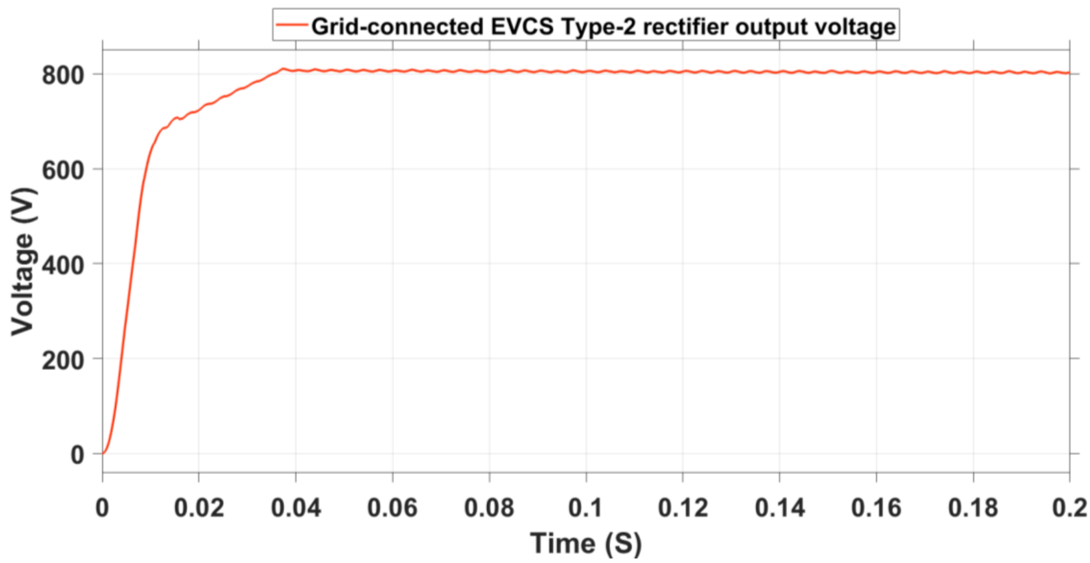

Figure 4.17. Grid-connected EVCS rectifier output voltage (type-2).

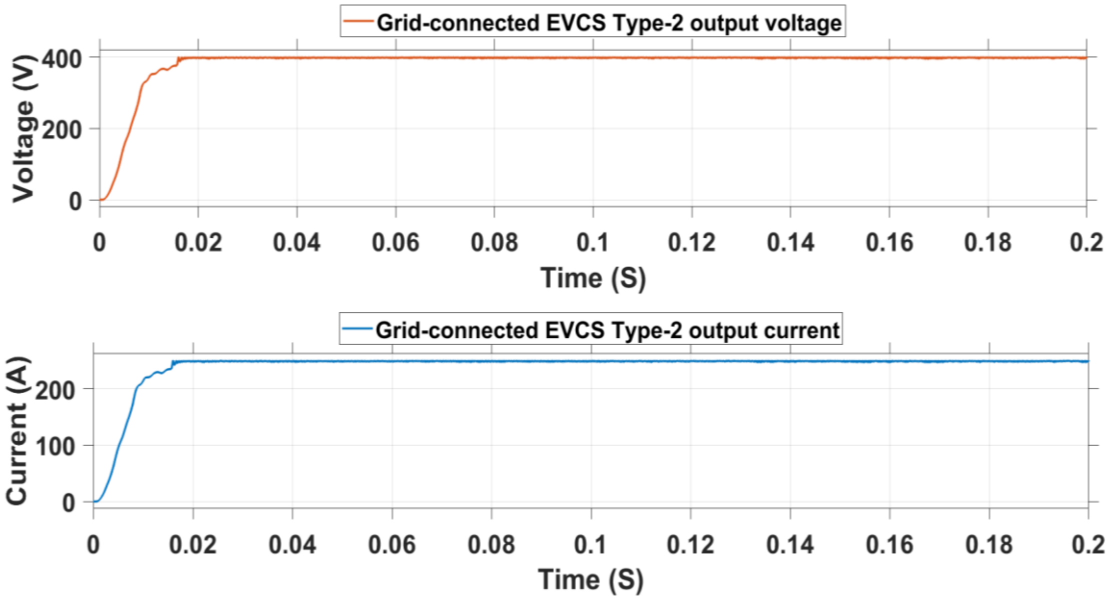

Figure 4.18. Grid-connected EVCS output voltage & current (type-2).

In comparison between EVCS type-1 and type-2 in terms of performance in the grid-connected scenario, it can be noticed that type-1 perform better in both transient and steady state. For that, a preliminary conclusion can be made that from design point view, type-1 is recommended to be installed if the utility grid to select among these two types. However, this not the only performance constraint and a comparison analysis between system parameters results in both cases.

4.4.1 Impact on THD

Total harmonic distortion contents of line voltage at EVCS-connected buses are shown in Figure 4.19 to Figure 4.23. it can be seen from the results that bus 12 achieve the maximum THD level as it shown in Figure 4.21 giving tight margin for penetration of more EV charging stations or any type of non-linear load that may cause the bus voltage to go beyond the standard limit. On the other hand, Figure 4.23 show that bus 6 THD result in 2.48% of the fundamental component and hence, more EVs can be charged from that bus.

In the other three buses, THD level varies between 2.52% at bus 10, 2.72% at bus 15 and lastly 2.73% at bus 5. The results for bus 5,15 and 10 are shown in Figure 4.19, 4.20 and 4.22 respectively.

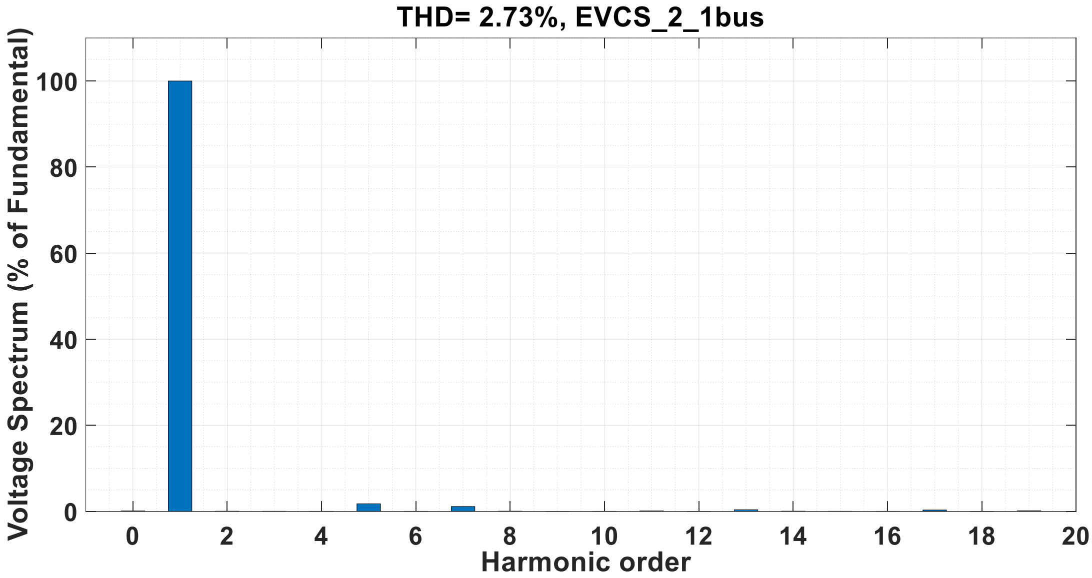

Figure 4.19. THD level at EVCS_2_1 bus (type-2).

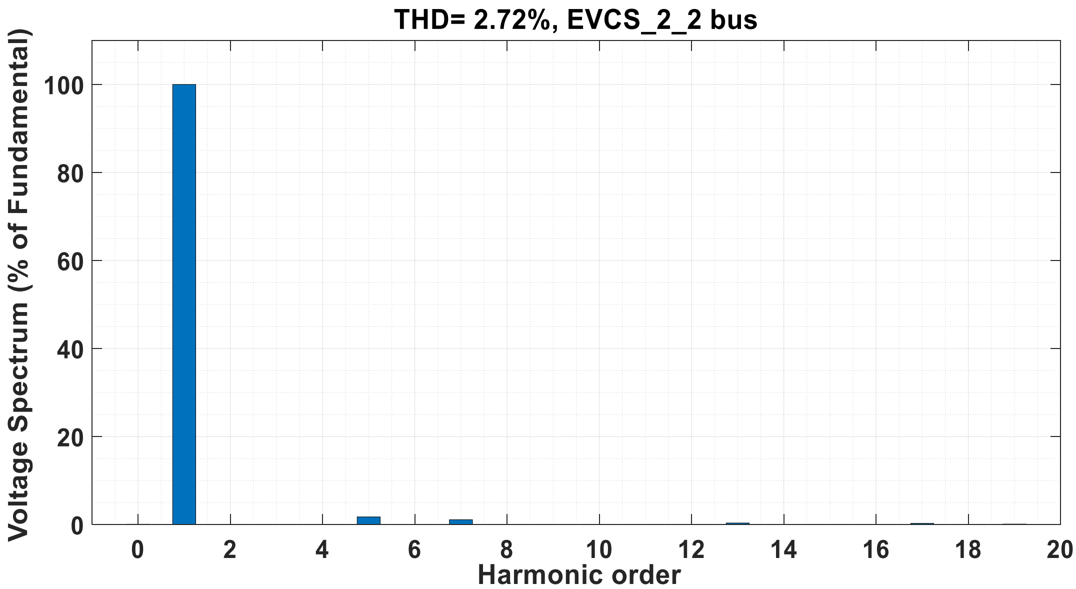

Figure 4.20. THD level at EVCS_2_2 bus (type-2).

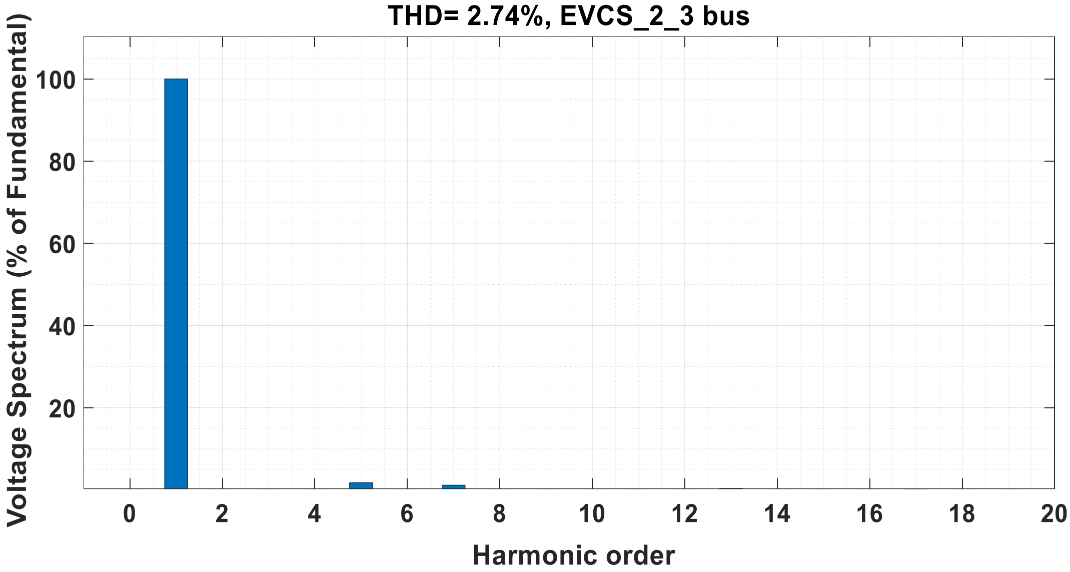

Figure 4.21. THD level at EVCS_2_3 bus (type-2)

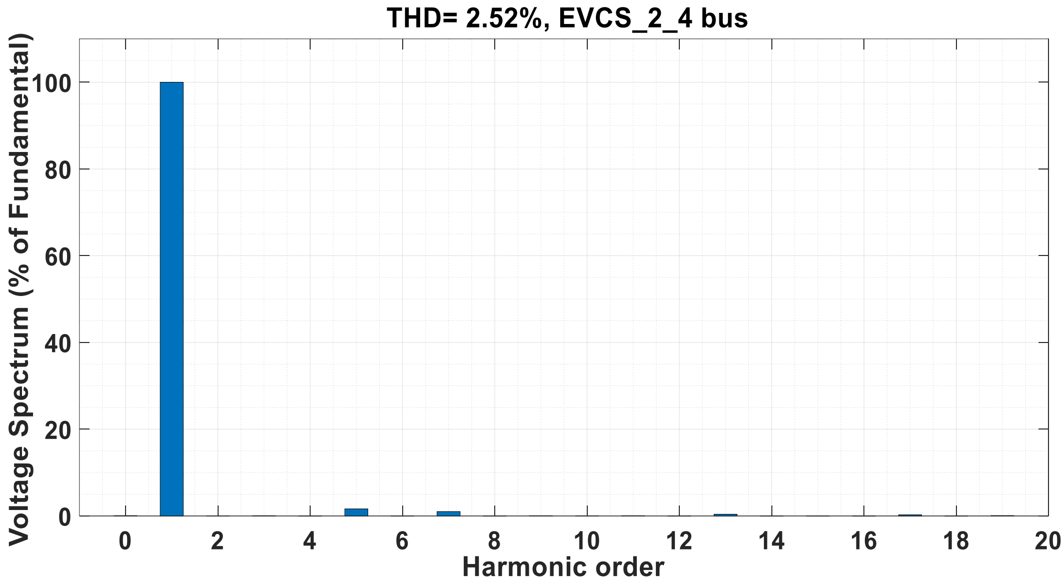

Figure 4.22. THD level at EVCS_2_4 bus (type-2).

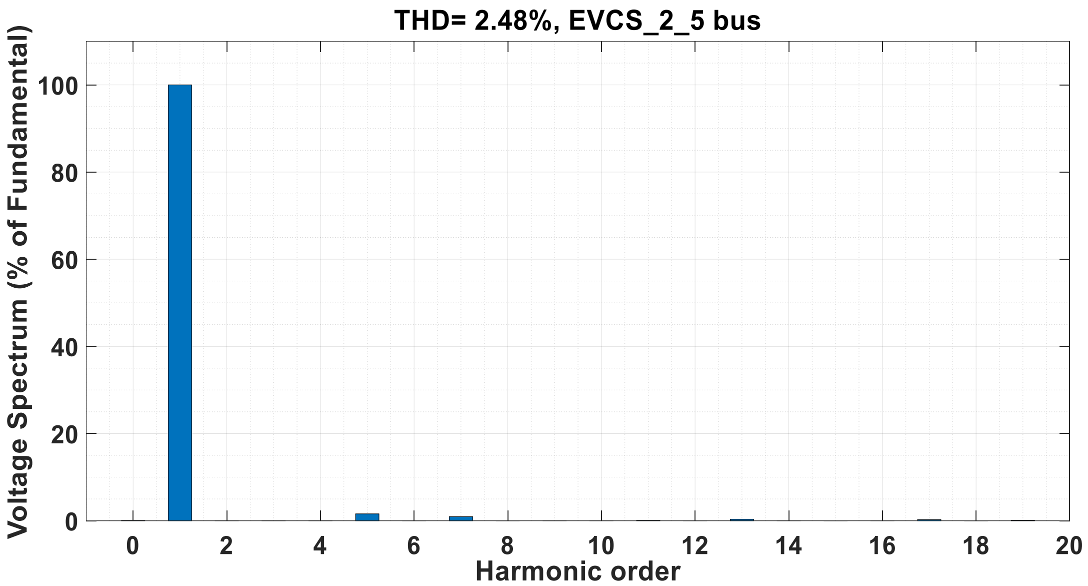

Figure 4.23. THD level at EVCS_2_5 bus (type-2).

From the results presented above, it can be noticed that unlike type-1 which THD level was in range of 3%-4%, type-2 experiences less THD level that varies from 2.48% up to 2.74%. therefore, type-2 once it is connected to the grid performs better than type-1 in terms of harmonic distortion contents and hence it is recommended to install this EVCS combination at buses where THD level allowable range is very tight in contrast to type-1. However, in residential areas the main source of harmonic is electronic devices and usually they are classified as extra low voltage and low power loads and hence the Kahramaa distribution feeders that supply residential loads will experience less THD level in comparison to industrial or commercial loads. Summary of THD level for EVCS type-2 is given in table 4.6.

Table 4.6. THD Level Summary (EVCS Type-2)

Bus No	THD (%)
EVCS_2_1	2.73
EVCS_2_2	2.72
EVCS_2_3	2.74
EVCS_2_4	2.52
EVCS_2_5	2.48

4.4.2 Impact on Voltage drop

In terms of voltage drop at the buses where EVCS is connected, type-2 performance varies from slightly below 550V up to 576.4V. the results are shown in Figure 4.24 to Figure 4.28. in Figure 4.26, bus 12 experiences severe voltage drop where the peak value reaches 540.4 V and in Figure 4.28 bus 6 hit 549.4 V. Moreover, in Figure 4.27 bus 10 gives the least voltage drop where the peak line voltage drop to 576.4 V in comparison to buses 5 and 15 with 567.9 V and 567.6 V respectively. The resulted voltage waveform for bus 5 is given in Figure 4.24 while for bus 15 is shown in Figure 4.25. Looking at voltage signal at the EVCS-connected buses, it can be seen that in the transient period, the voltage drops down to 500 V for almost half cycle before it reaches its steady state values. This is important note because neglecting this drop may result in false trip of the protection device that is sensitive to severe voltage drop during transient.

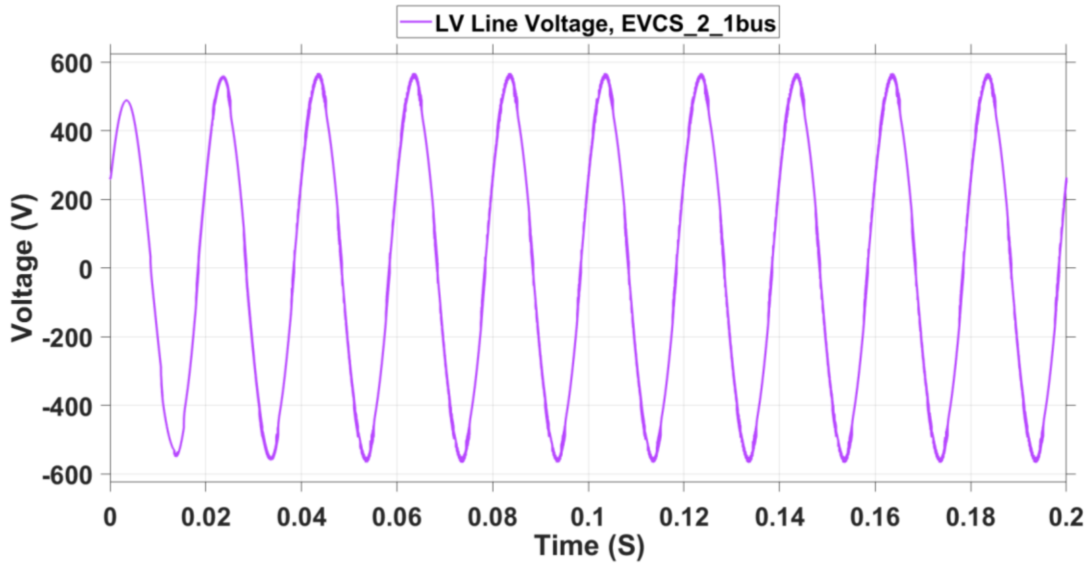

Figure 4.24. LV line voltage at EVCS_2_1 bus (type-2).

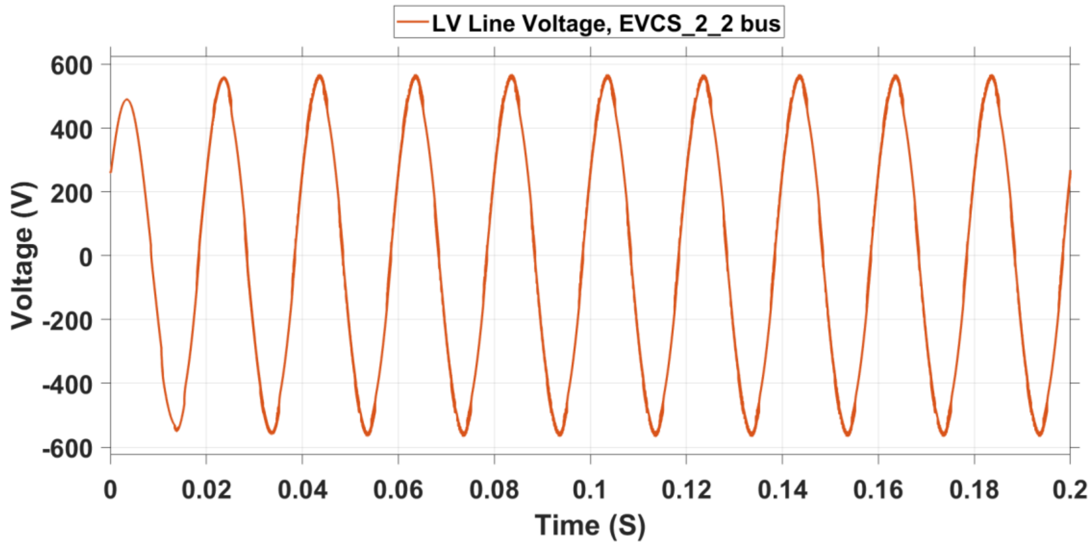

Figure 4.25. LV line voltage at EVCS_2_2 bus (type-2).

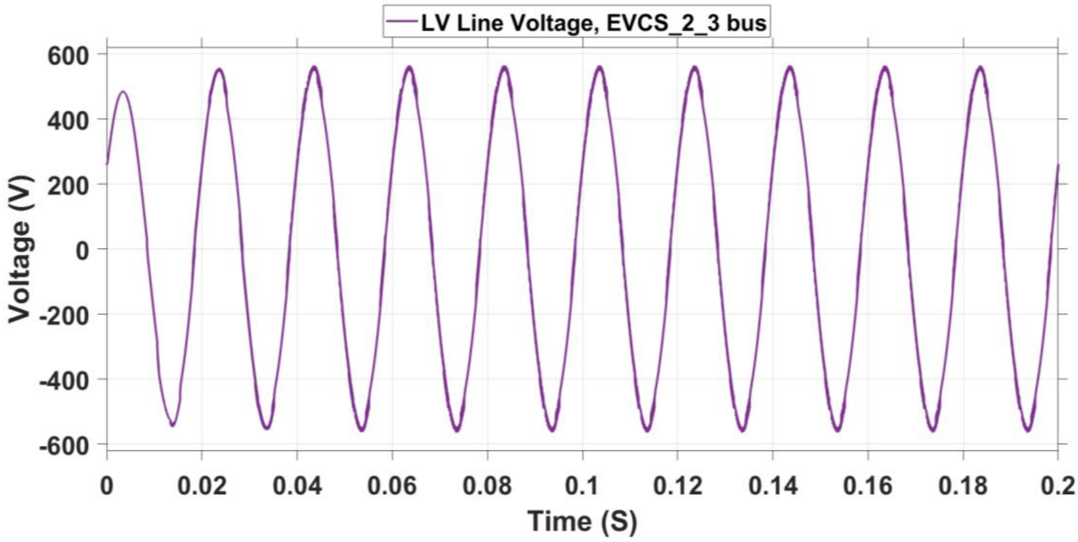

Figure 4.26. LV line voltage at EVCS_2_3 bus (type-2).

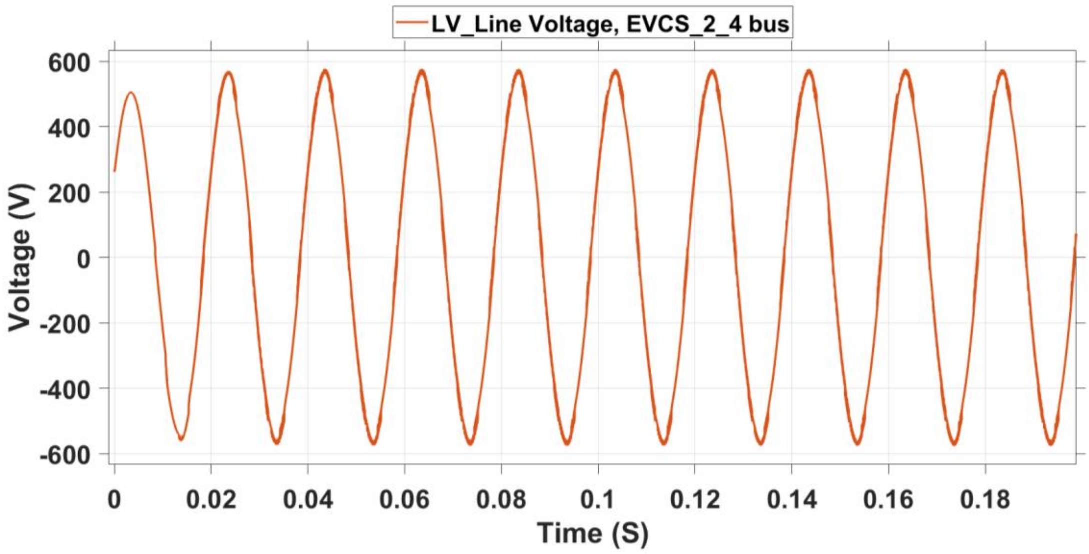

Figure 4.27. LV line voltage at EVCS_2_4 bus (type-2).

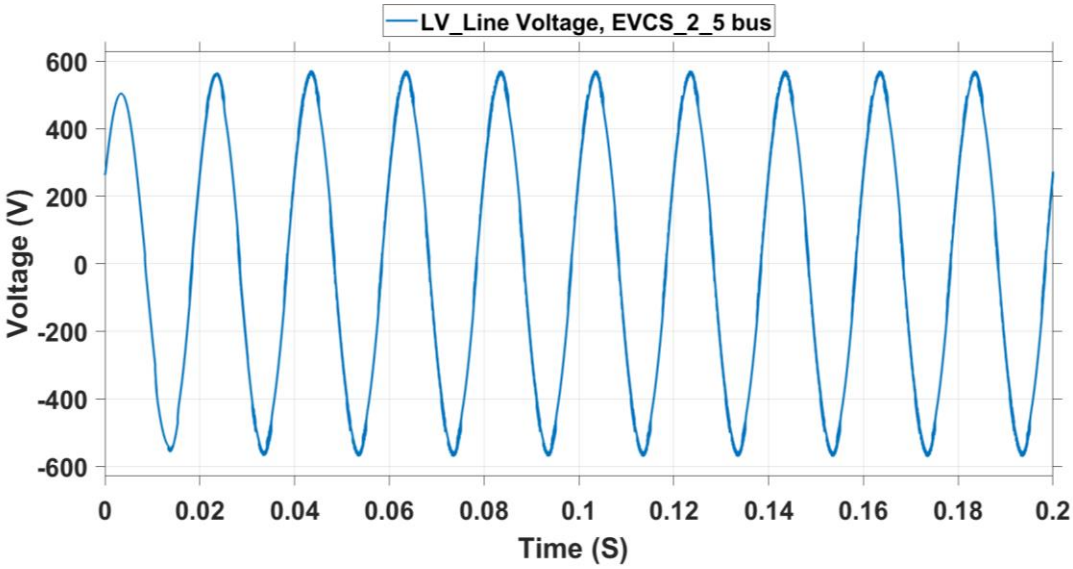

Figure 4.28. LV line voltage at EVCS_2_5 bus (type-2).

From the results, it can be concluded that buses 12 and 6 violates the standard voltage limit imposed by Kahramaa which is 551.68V and for that EV charging stations cannot be installed at these buses at the present scenario. The other three buses experience voltage drop within the acceptable range. Bus 12 is the optimal place for the installation of EVCS if the voltage-drop criteria to be considered. There are several causes for this high drop and among these reasons is sensitivity of the bus due to heavy loads or long feeders. In order to combat this challenge, alternative source can be integrated near the load in order to supply the required load and hence, reduce the voltage drop on the public common coupling point. In addition to that, another run of feeders may install in parallel with the existing one in order to decrease the overall line impedance and that will mitigate the voltage drop to be within the approved range. Voltage peak values at the investigated buses are summarized in table 4.7.

Table 4.7. Line Voltage Peak Values (EVCS Type-2)

Bus No	Line Voltage (V)
EVCS_2_1	567.9
EVCS_2_2	567.6
EVCS_2_3	540.4
EVCS_2_4	576.4
EVCS_2_5	549.4

4.4.3 Impact on Line and Total Losses

Line and system total losses is the third parameter that is investigated when EVCS type-2 is connected to the system. Table 4.8 summarizes the results where the percentage of total losses varies from 1.44% in the line 11-12 down to 0.05% in the line 6-8. Moreover, the total system losses increase by 2.44% while line 11-12 experiences the largest increase among the other feeders where the EV charging stations are connected. On the other hand, the smallest line losses percentage increase is found in feeder 6-8 where the losses increase from 0.0281kW to 0.3909kW. feeders 9-10 and 4-15 suffer almost the same line losses increase with 0.40% for feeder 4-15 and 0.41 within feeder 9-10. Lastly, feeder 4-5 losses increase from 0.20869 kW to 0.2525 kW with 0.38% increase.

Table 4.8. Line & Total Losses Results (EVCS Type-2)

EVCS_2 Line No.	Line Losses (kW)	Losses Increase (kW)	Percentage of Total Losses (%)
4-5	0.2525	0.20869	0.38
4-15	0.306	0.22006	0.40
11-12	1.994	0.798	1.44
9-10	0.2744	0.2249	0.41
6-8	0.3909	0.0281	0.05
Total Losses	56.812	1.354	2.44

In comparison between EVCS type-1 and type-2 in terms of line and system losses, it can be observed that the system performance is almost the same with slight differences that have not effected the overall similarity. Feeder 11-12 suffers the largest losses in both cases where the percentage of total losses is 1.69% in type-1 and 1.44% in type-2. The total percentage losses are the same for both types and this indicates that either types can be installed without any significant difference in system performance in terms of line and network total losses. the main reason for this similarity is that the total proposed load for the five EVCSs of each type is 500 kW distributed in the network and because the existing load remains the same for both cases, the EVCS-connected feeders result in approximately the same losses.

In the next section EVCS type-3 performance is examined and distribution network is evaluated again in terms of THD level, voltage drop and losses in order to conclude the overall comparison analysis for the three types.

4.5 Impact of Type-3 Charging Station

The third type of EV charging stations that has been simulated in this study is a combination of front-end rectifier along with phase-shifted full bridge DC-DC converter. Figure 4.29 shows the location buses where EVCS type-3 five numbers are connected. All the types are rated at 415 V, 50 Hz and to supply 100 kW load at 400 V. the EV charging stations are connected to 11kV/415V, 1600 kVA distribution transformers at the targeted LV buses. The main three phase source is simulated to model 40 MVA Kahramaa standard primary substation and bus 2 serve as main 11kV switchgear with three feeders that supply three different areas.

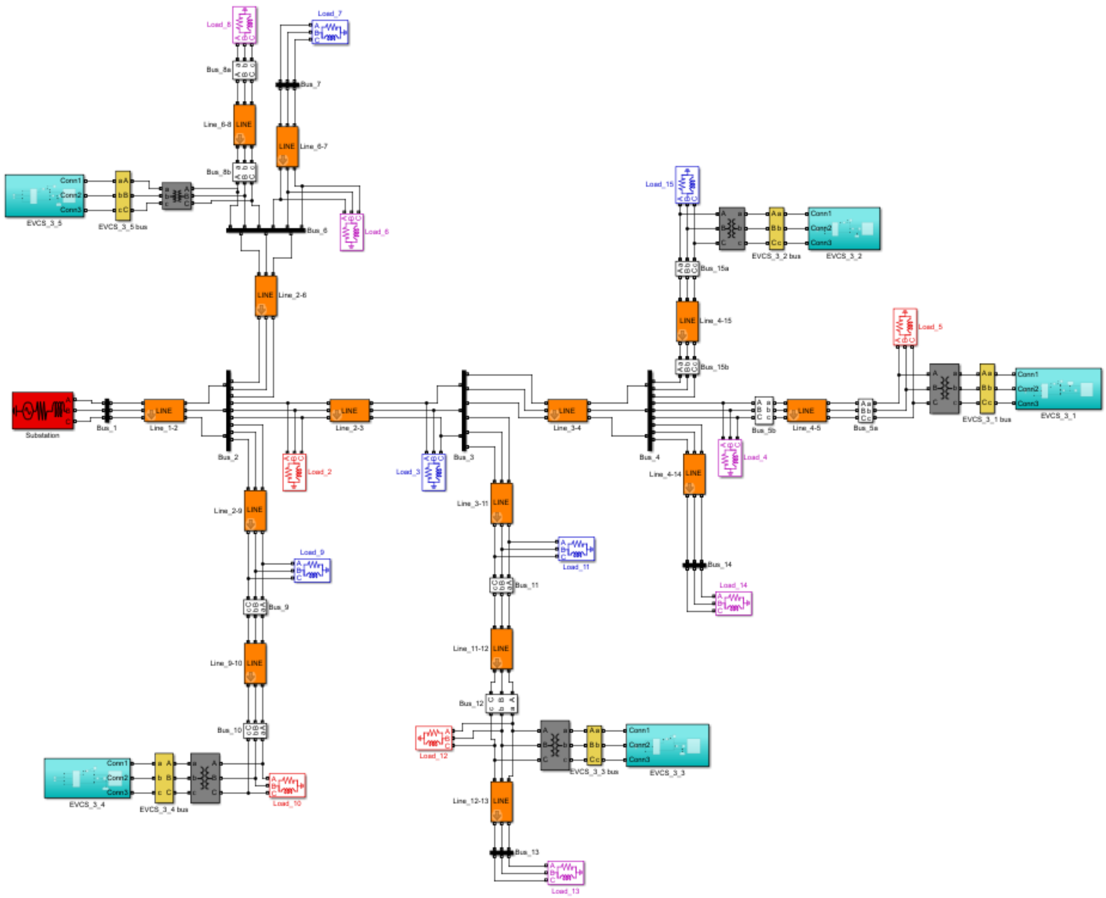

Figure 4.29. EVCS-connected distribution network (type-3).

Figure 4.30 shows EVCS rectifier output voltage where the signal experiences long transient period with overshooting that went above 1200V and lengthy settling time that last for 0.08s. the signal reaches steady state with non-zero steady state error and fluctuating wave. On the other hand, load output voltage and current are shown in Figure 4.31 where they perform well in the steady state period with almost clean DC outputs.

However, one can observe V-shape drop below the targeted value in the time range from 0.03s to 0.05s and the main obvious cause is the sever drop in the rectifier output voltage during the same time. Although the load voltage and current suffer this V-shape drop after they reach their final steady state values at approximately 0.01s, the time range from 0 to 0.05s is considered as transient period due to long settling time in the rectifier output voltage. The main reason for this phenomena as observed in chapter 3 is the control sensitivity to voltage drop and that need to be taken into consideration during the selection of protection devices.

Next sections discuss the network performance in terms of voltage THD level, voltage drop as well as line and system losses when EVCS type-3 is installed.

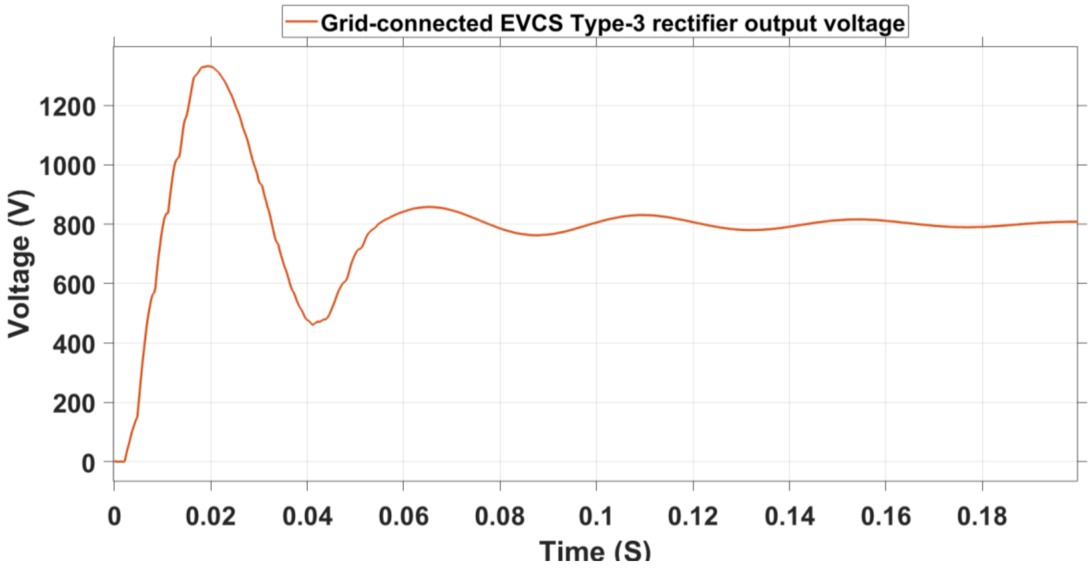

Figure 4.30. Grid-connected EVCS rectifier output voltage (type-3).

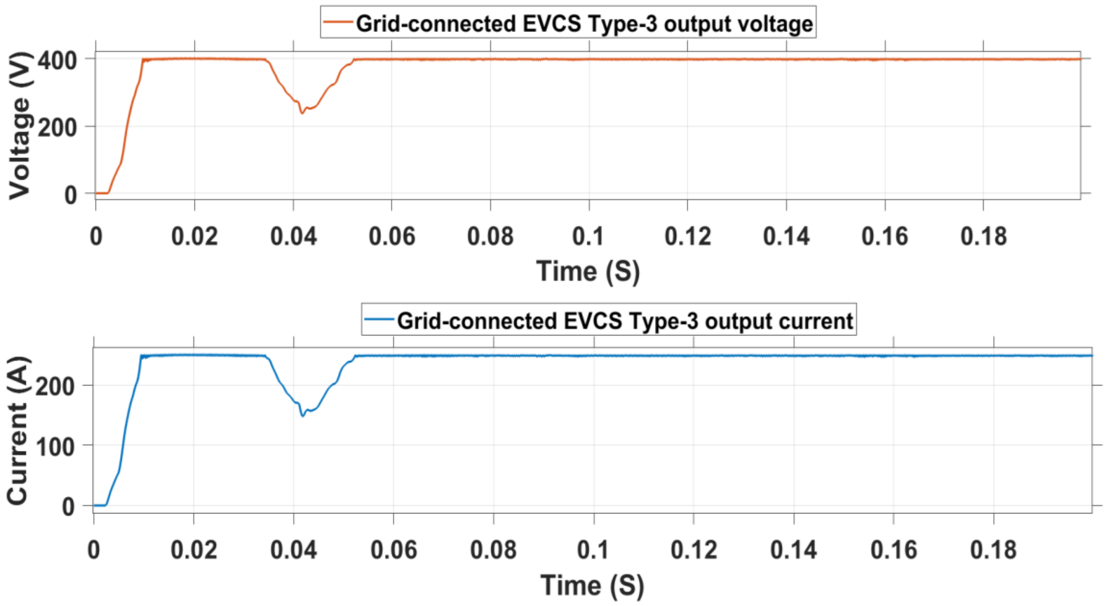

Figure 4.31. Grid-connected EVCS output voltage & current (type-3).

4.5.1 Impact on THD

The first parameter examined is harmonic distortion of the line voltage at EVCS-connected buses and the spectrum results in Figure 4.32 to Figure 4.36. From the results, it can be observed that THD values are below 1% which shows that type-3 perform well in terms of THD levels. In Figure 4.34, bus 12 has the maximum THD percentage of 0.38% among other buses connected to EVCS type-3. However, bus 10 and bus 6 score the least THD level with 0.28% and 0.27% as it is shown in Figure 4.35 and 4.36 respectively. Figure 4.32 shows THD level of 0.36% for bus 5 while in Figure 4.33 0.35% for bus 15. It worth noting that THD level for EVCS typ-3 in the transient period is very high and it reaches 17% level. However, the presented values are measured after few cycles in order to examine system performance during steady state.

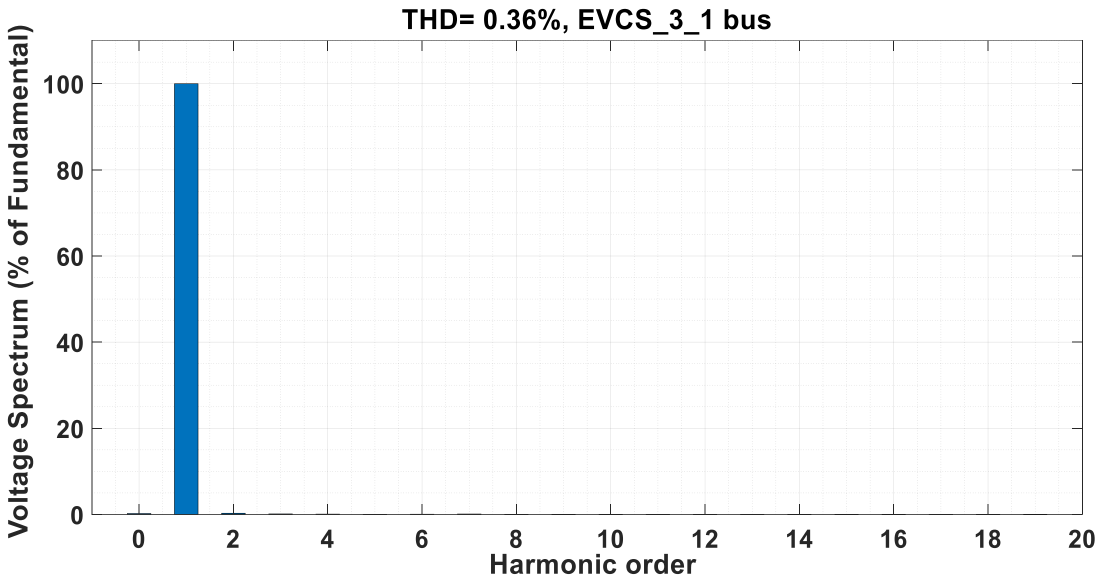

Figure 4.32. THD level at EVCS_3_1 bus (type-3).

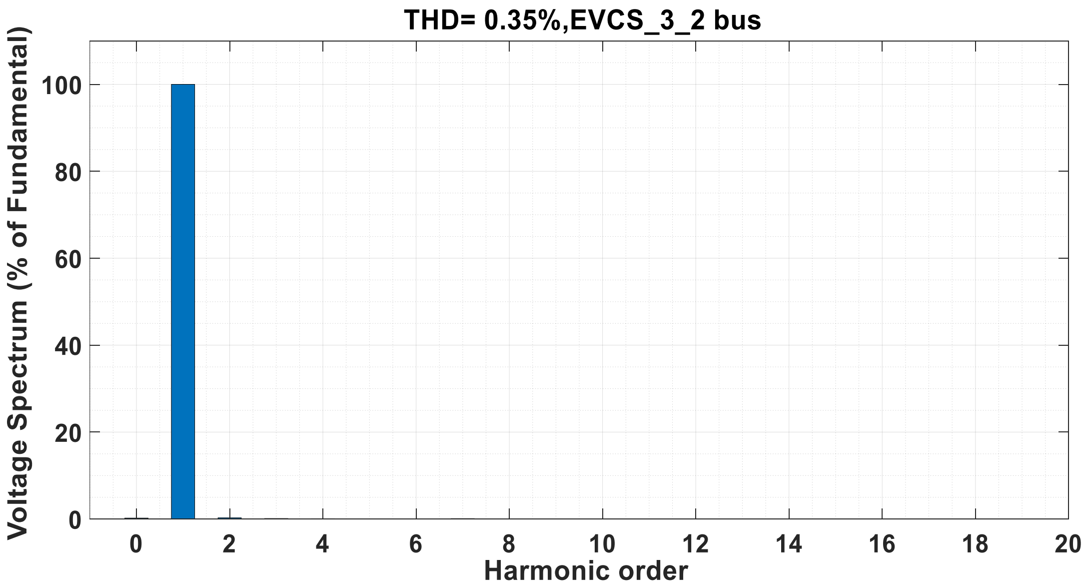

Figure 4.33. THD level at EVCS_3_2 bus (type-3).

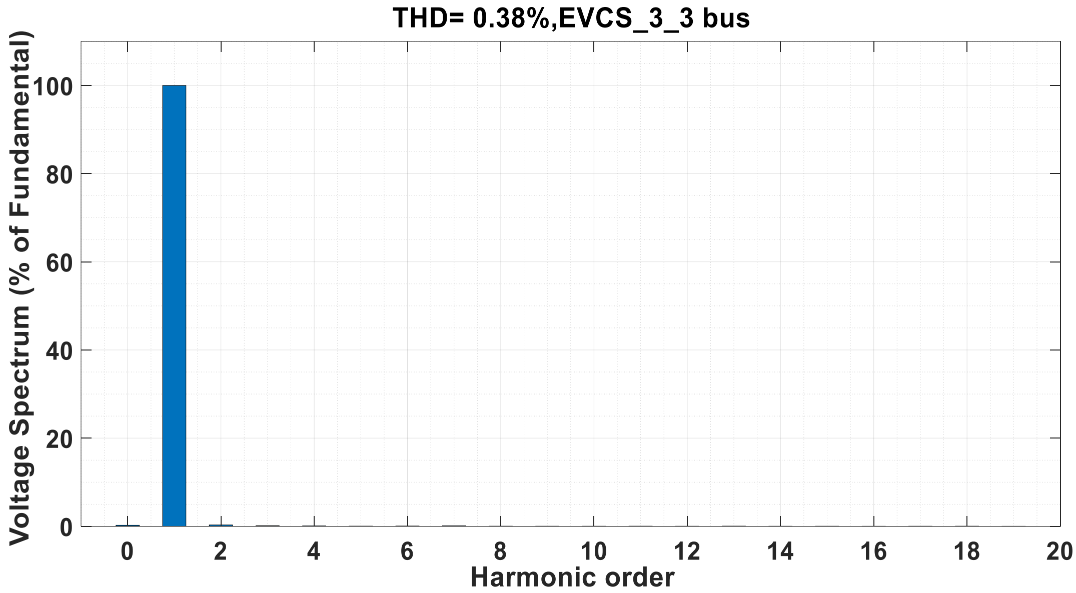

Figure 4.34. THD level at EVCS_3_3 bus (type-3).

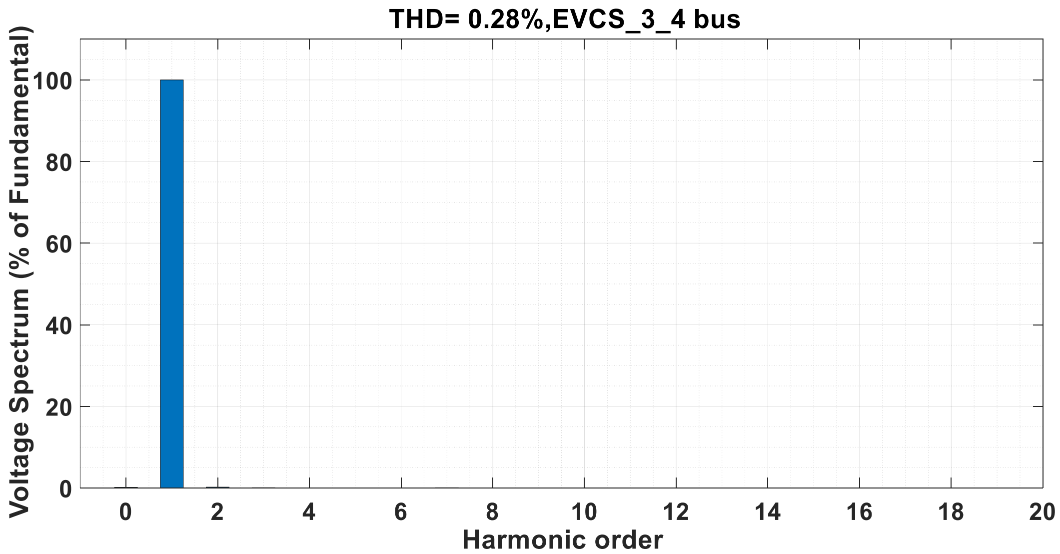

Figure 4.35. THD level at EVCS_3_4 bus (type-3).

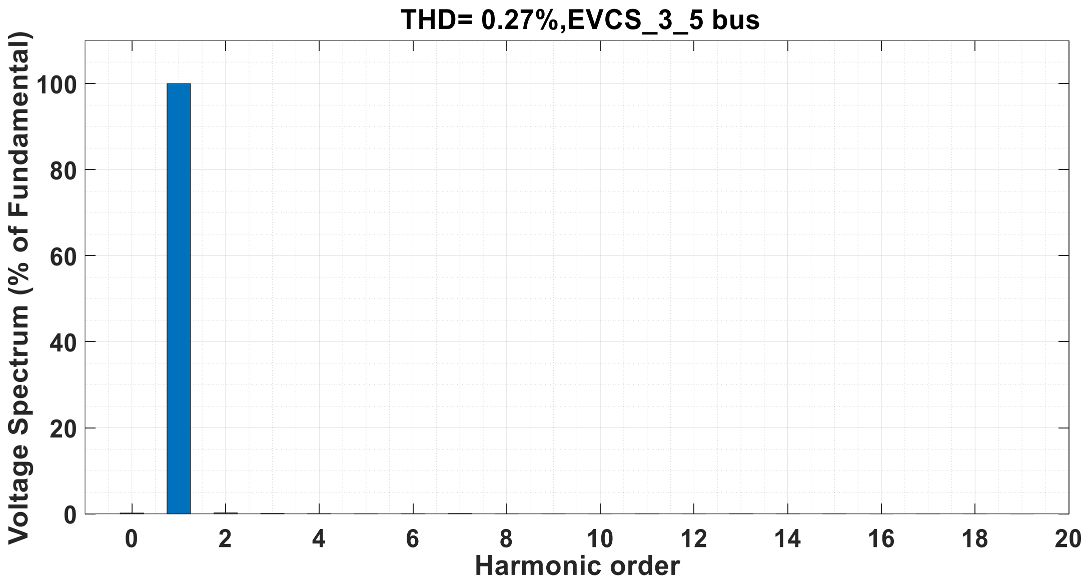

Figure 4.36. THD level at EVCS_3_5 bus (type-3).

In comparison with the previous EVCS types, type-3 achieved the best performance among the three in terms THD levels and hence for the residential or commercial areas with large non-linear loads, EVCS type-3 is recommended. Moreover, if higher rated EVCS is required to be installed at specific bus, large number of type-3 can be connected to that bus with load sharing control strategy. However, other parameters such as voltage drop and line losses need to be investigated before allowing supplier to install high rated power EV charging stations because these parameters may exceed the standard limit. Table 4.9 summarize type-3 THD results.

Table 4.9. THD Level Summary (EVCS Type-3)

Bus No	THD (%)
EVCS_3_1	0.36
EVCS_3_2	0.35
EVCS_3_3	0.38
EVCS_3_4	0.28
EVCS_3_5	0.27

4.5.2 Impact on Voltage drop

Line voltage waveforms of the EVCS-connected buses are shown in Figure 4.37 to Figure 4.41 where the expected peak value is 586.9V. however, the resulted values vary from 556.8 V to 568.7 V where bus 10 shows the minimum voltage drop with peak value of 568.7 V is it shown in Figure 4.40. on the other hand, in Figure 4.39, bus 12 voltage signal drops down to 556.8 V giving less margin for higher rating of EVCS installation. Bus 5 and bus 15 score the same voltage drop and the peak value reaches 560.5 V as in Figure 4.37 and Figure 4.38 respectively. lastly, in Figure 4.41 voltage signal of bus 6 is shown with 564.6 V peak value. When the waveform is examined closely, it can be noticed that the time range from 0 to 0.04s, the signal is highly distorted and hence this time period need to be taken into consideration during protection device selection process. It can be observed that this contamination portion is corresponding to the severe voltage drop occurred in rectifier output voltage during transient.

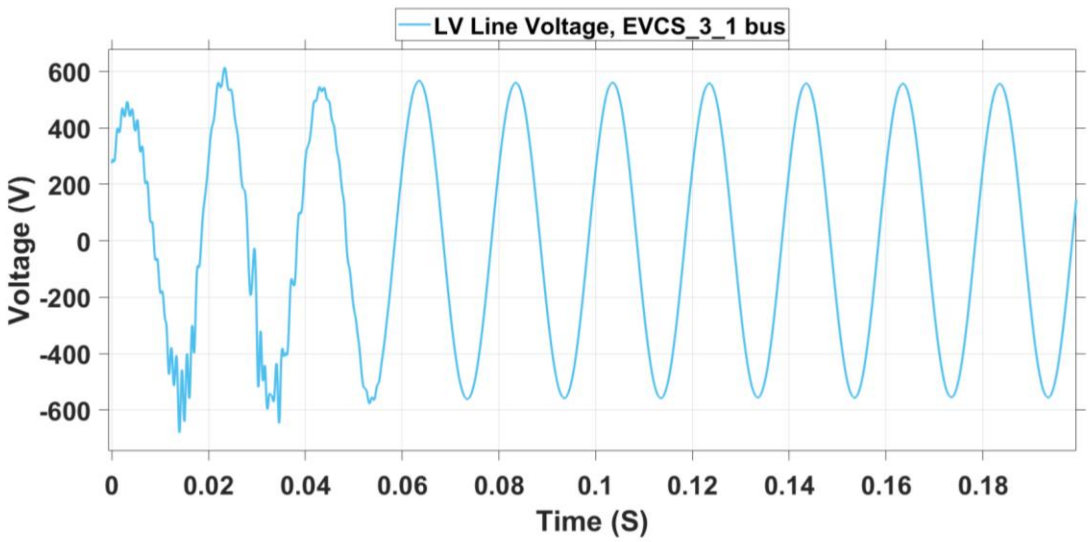

Figure 4.37. LV line voltage at EVCS_3_1 bus (type-3).

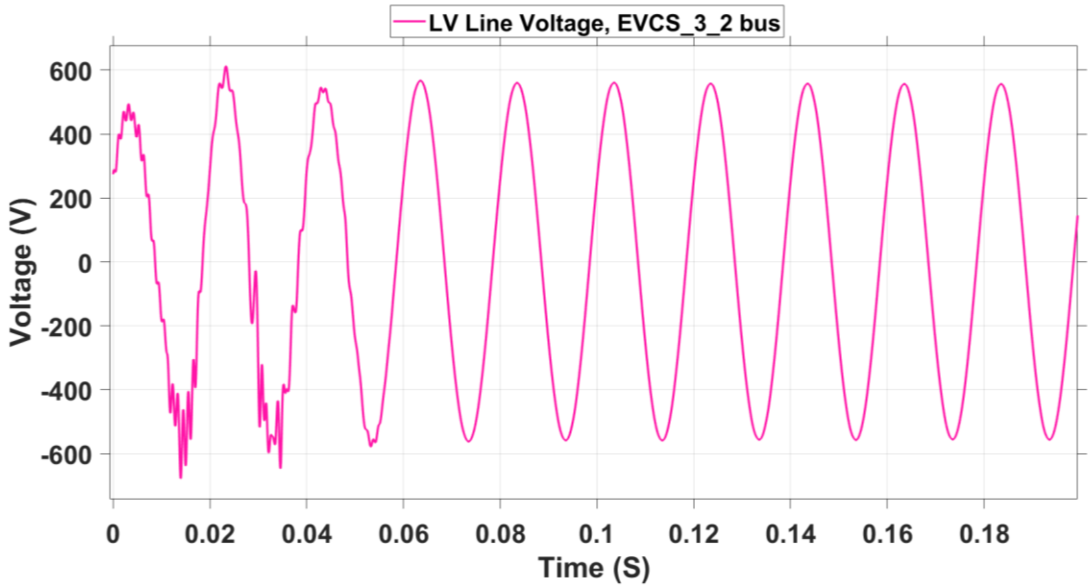

Figure 4.38. LV line voltage at EVCS_3_2 bus (type-3).

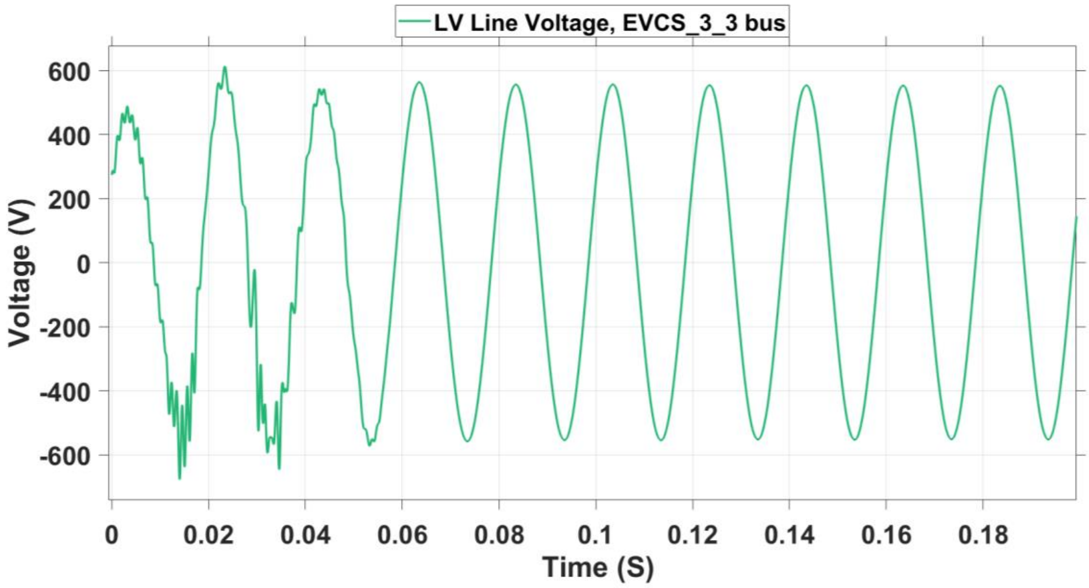

Figure 4.39. LV line voltage at EVCS_3_3 bus (type-3).

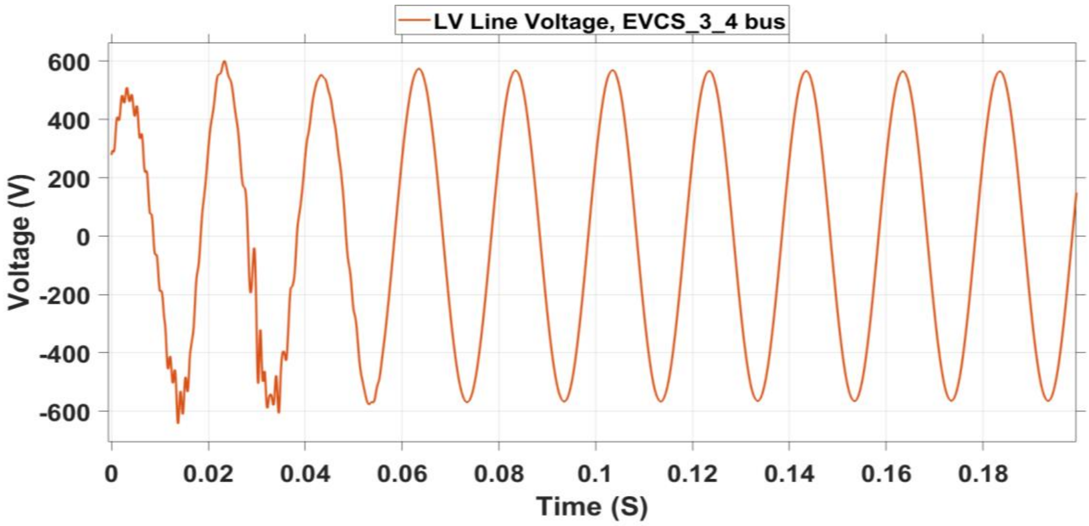

Figure 4.40. LV line voltage at EVCS_3_4 bus (type-3).

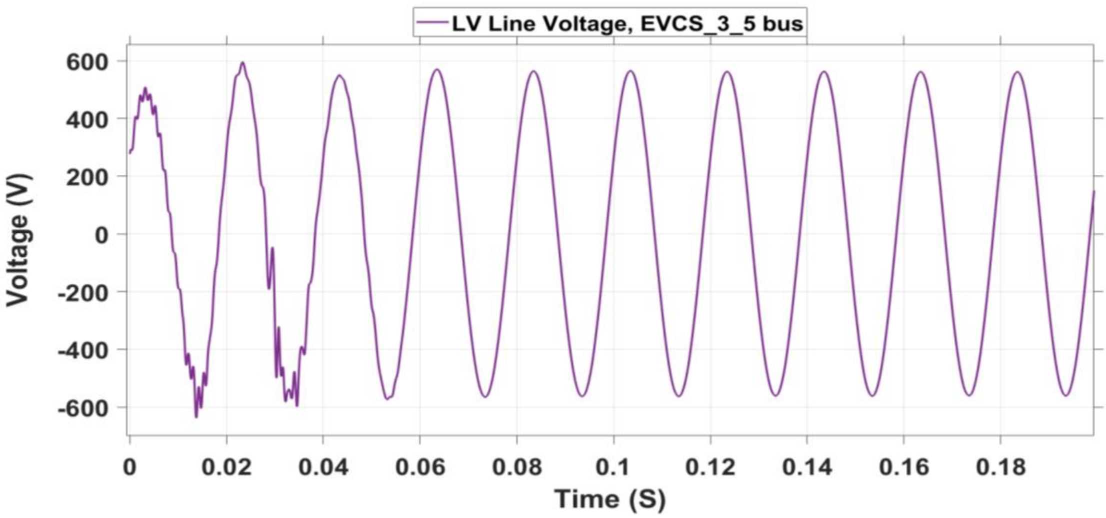

Figure 4.41. LV line voltage at EVCS_3_5 bus (type-3).

Unlike Type-2 where some of buses violate kahramaa standard limit, EVCS of type-3 perform well within the acceptable range and hence all the tested buses can be utilized to increase EVCS penetration level. However, kahramaa uses tap-changing distribution transformers in case of severe voltage drop in order to raise the line voltage to the standard especially in remote urban areas. For that, EVCS with higher power rating can be installed in these areas and raise the taping point voltage to be within the limit. Summary of EVCS type-3 bus line voltage peak values is given in table 4.10.

Table 4.10. Line Voltage Peak Values (EVCS Type-3)

Bus No	Line Voltage (V)
EVCS_3_1	560.5
EVCS_3_2	560.5
EVCS_3_3	556.8
EVCS_3_4	568.7
EVCS_3_5	564.6

4.5.3 Impact on Line and Total Losses

Lastly, line and system total losses are investigated EVCS-connected buses of type-3 and results summarized in table 4.11. Like the previous EVCS types, feeder 11-12 exhibits the maximum loss with 1.35% of the total losses while feeder 6-8 shows the least line losses with value of 0.03%. moreover, system total losses increase slightly in comparison with type 1 and 2 and hence indicates that EVCS type 3 is performed well in terms of system losses. the same conclusion cannot be said to the line losses where the three types behave in the same manner with small deviation which has not impact the overall network performance.

Table 4.11. Line & Total Losses Results (EVCS Type-3)

EVCS_3 Line No.	Line Losses (kW)	Losses Increase (kW)	Percentage of Total Losses (%)
4-5	0.3216	0.27779	0.50
4-15	0.3228	0.23686	0.43
11-12	1.944	0.748	1.35
9-10	0.3227	0.2732	0.49
6-8	0.3815	0.0187	0.03
Total Losses	55.651	0.193	0.35

At the end of this chapter, brief summary of network examined parameters evaluation is given in table 4.12, 4.13 and 4.14 in terms of THD, line peak voltage and line losses respectively. From utility perspective, this summary can be observed from several dimensions depends on the selected parameter, EVCS type as well as supply feeder.

Table 4.12. THD Comparison Summary for all EVCS Types

Line (bus No)	EVCS Type-1 THD (%)	EVCS Type-2 THD (%)	EVCS Type-3 THD (%)
4-5 (bus 5)	3.68	2.73	0.36
4-15 (bus 15)	3.66	2.72	0.35
11-12 (bus 12)	3.68	2.74	0.38
9-10 (bus 10)	3.44	2.52	0.28
6-8 (bus 6)	3.35	2.48	0.27

Table 4.13. Line Peak Voltage Comparison Summary for all EVCS Types

Line (bus No)	EVCS Type-1 Line Voltage (V)	EVCS Type-2 Line Voltage (V)	EVCS Type-3 Line Voltage (V)
4-5 (bus 5)	561.9	567.9	560.5
4-15 (bus 15)	560.3	567.6	560.5
11-12 (bus 12)	557.4	540.4	556.8
9-10 (bus 10)	569.2	576.4	568.7
6-8 (bus 6)	562	549.4	564.6

Table 4.14. Power Losses Comparison Summary for all EVCS Types

Line (bus No)	EVCS Type-1		EVCS Type-2		EVCS Type-3	
	Losses (kW)	Increase	Losses (kW)	Increase	Losses (kW)	Increase
4-5 (bus 5)	0.32999		0.20869		0.27779	
4-15 (bus 15)	0.39186		0.22006		0.23686	
11-12 (bus 12)	0.938		0.798		0.748	
9-10 (bus 10)	0.1616		0.2249		0.2732	
6-8 (bus 6)	0.0115		0.0281		0.0187	
Total Losses Increase (kW)	1.354		1.354		0.193	

For instance, if the THD level is the main concern, EVCS type 3 shows the best performance when it is compared to other types with less than 0.5% level. Moreover, if the type 3 is selected, bus 6 is the optimal location for EV charging station installation. However, if the system loaded and feeders are supplying remote areas, then satisfying voltage drop limit is the major challenge. For that, EVCS type 2 shall be excluded at buses 12 and 6 because it suffers sever drop in the line voltage. However, among all choices, connecting type 2 at bus 10 is the optimal location in terms of voltage drop evaluation. Finally, from power losses perspective, system in general perform well with type 2 integration. nevertheless, type 3 is the optimal choice in terms of system total losses and bus 6 is the best location among all the buses for the three types with type 1 as the optimal selection where the line losses value is 0.0115% of total losses.

4.6 Summary

In this chapter, several EVCS types have been integrated into distribution system and system performance is investigated in terms of THD level, voltage drop and power losses at specified EVCS-connected busses. The results show that some types are the optimal selection from THD level perspective. However, performing well for one parameter is not guaranteed for the same type to be the optimal choice for other parameters.

Next chapter focuses on one feeder and integration of several combinations of EV charging stations along with renewable energy source will be investigated in terms of THD, voltage drop as well as system power losses.

Chapter 5: Impact of EVCS Penetration with RES on Distribution Feeder

5.1 Introduction

Unlike the previous chapter, this chapter focuses on one specific low voltage feeder where EV charging stations are connected. Two scenarios have been considered. Scenario 1 examine the feeder with the penetration of both EVCS single or multi types with absence of renewable energy source (RES). Secondly in scenario 2, the same process has been repeated with the integration of RES into the system.

5.2 Grid-connected EVCS impact on 415V-feeder

Firstly, EVCS of same type is integrated into 415 V feeder and that feeder performance is evaluated again in terms of harmonic distortion of line voltage, impact on voltage drop as well as line losses.

5.2.1 EVCS penetration Impact of one type on low voltage feeder

In the first part of scenario 1, 200 kW is connected through 11kV/415V distribution transformer with 1600 kVA rated power. As per Kahramaa practice, there are two types of distribution panels. The first one is feeder pillar where all the outgoing feeders are Kahramaa property and hence if the costumer requires to connected EVCS, Kahramaa is the authority to evaluate the impact of EVCS on its feeders and how it is going to effect the other connected loads belonging to different clients. However, in newly implemented practices, Kahramaa asked the bulk customers that requiring higher power rated EVCS to install dedicated LV panel where this panel serves one customer only. In that case, client is responsible to limit the impact of its installed charging station to be in accordance with Kahramaa rules and regulations. Figure 5.1 shows the connection of EVCS type 1 into line 4-5 and type 2 and 3 typically the same.

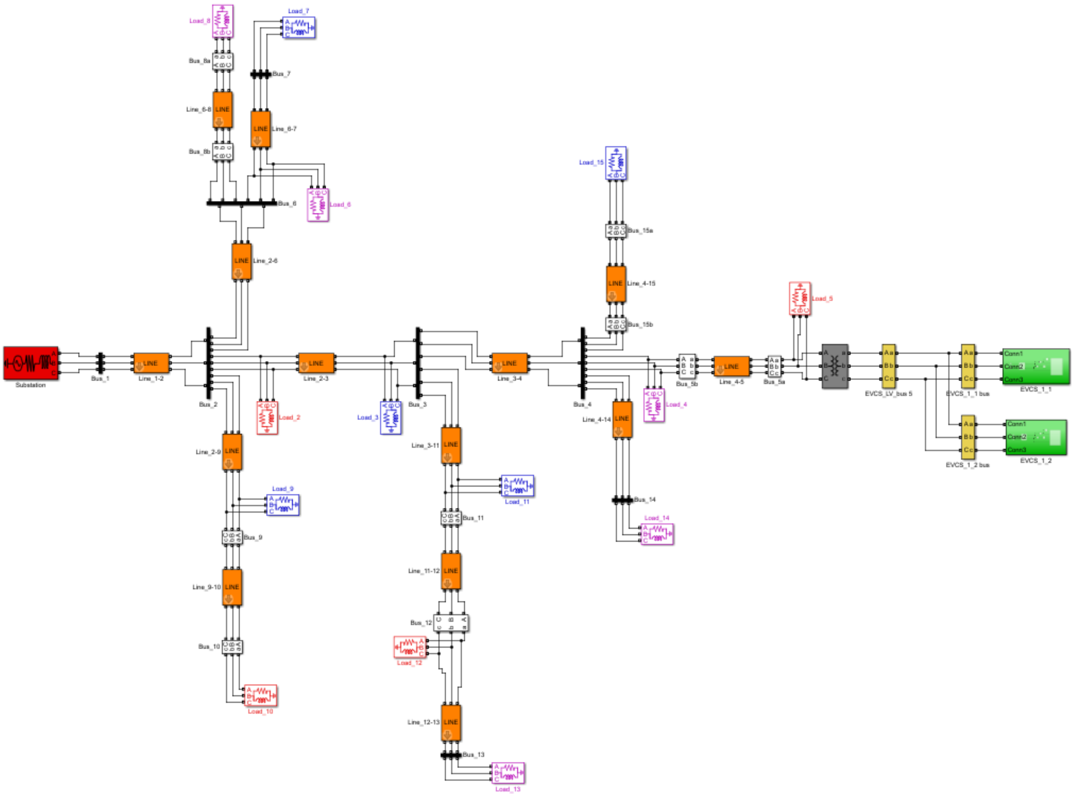

Figure 5.1. EVCS-connected LV feeder (type-1).

5.2.1.1 Impact on THD level

First system parameter that has been tested is total harmonic distortion and from Figure 5.2 it can be seen that EVCS type 1 went beyond the standard limit with 5.57% which indicates that LV feeder is sensitive to this type and hence only one fast charging 100kW EVCS can be connected to this feeder. However, type 2 experience THD level of 2.58% as shown in Figure 5.3 with 200kW installed. Moreover, type 3 demonstrate the optimal selection among the three types from THD level perspective with 0.5% as in Figure 5.4 giving 4.5% margin for more EVCS penetration at feeder 4-5. It can be inferred that more than 1000kW of type 3 may install into the feeder without violating THD standard limit. However, before installing this large charging station, other parameters need to be investigated to ensure they are all within the acceptable range.

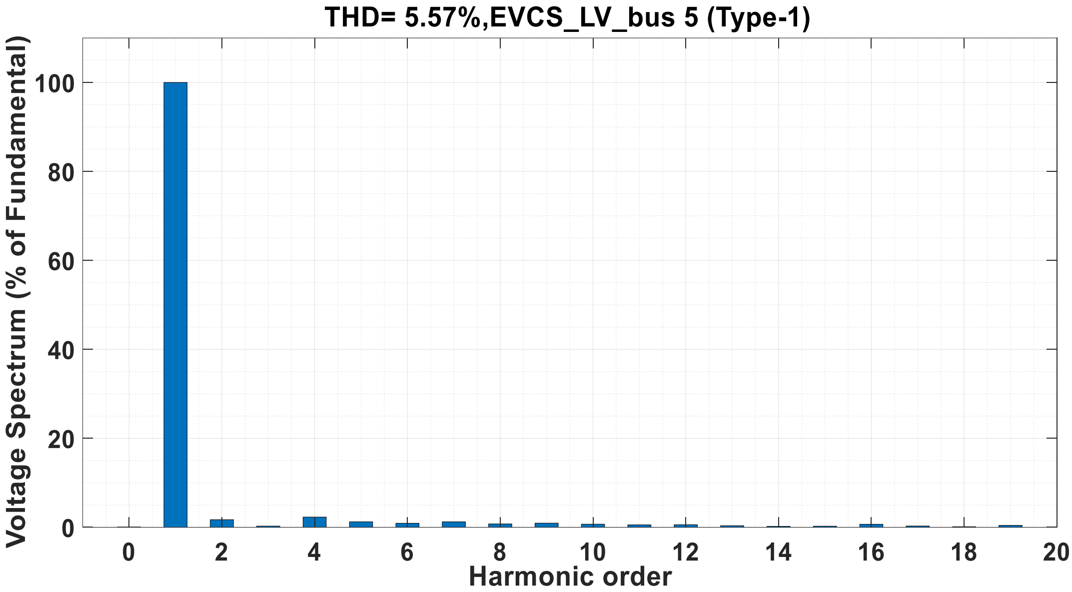

Figure 5.2. THD level at EVCS_LV_bus 5 (type-1).

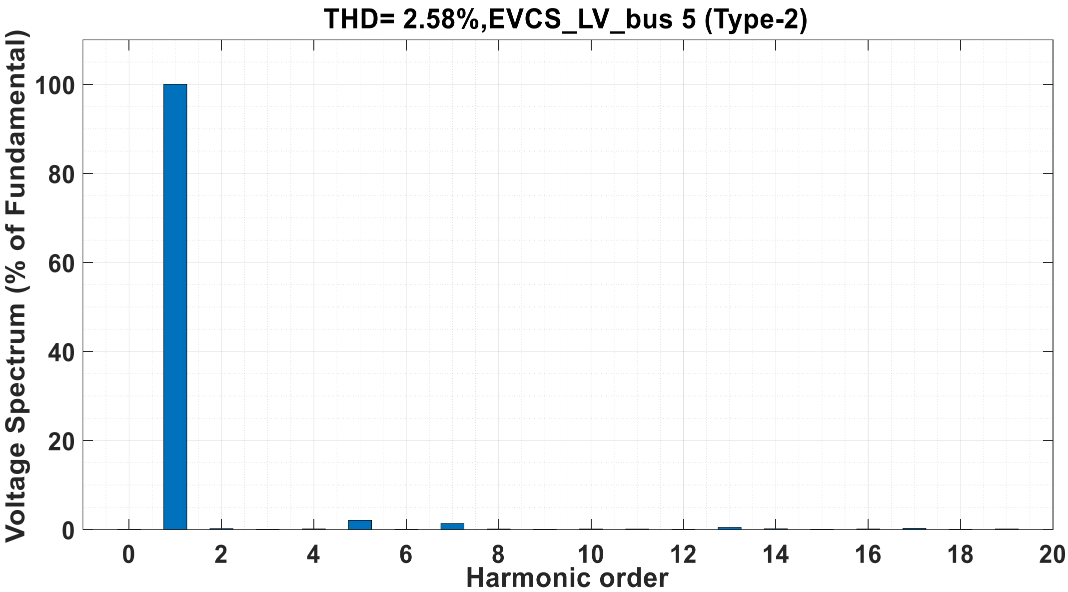

Figure 5.3. THD level at EVCS_LV_bus 5 (type-2).

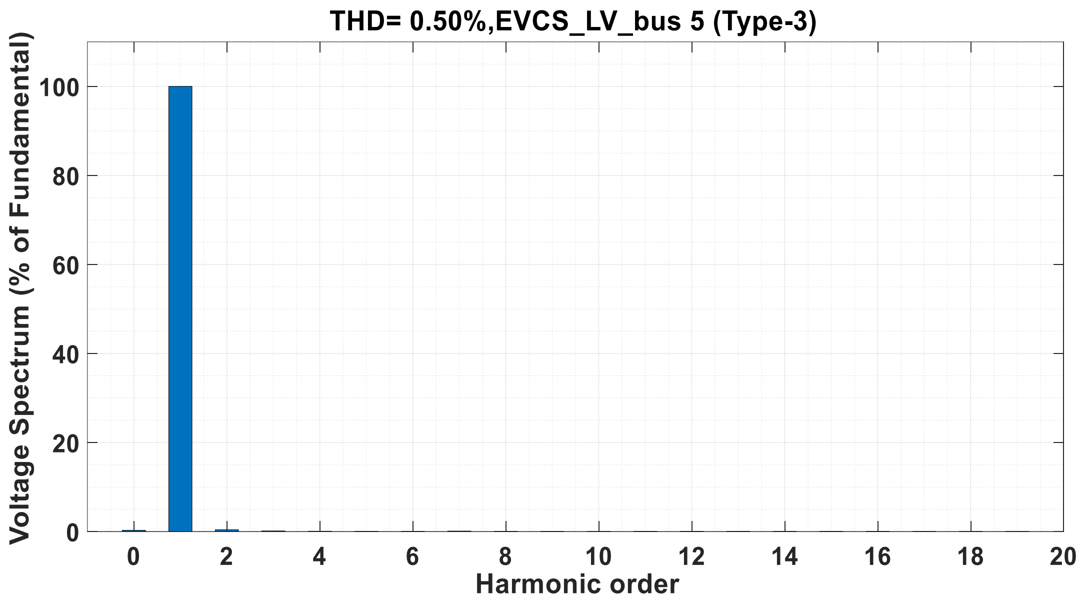

Figure 5.4. THD level at EVCS_LV_bus 5 (type-3).

5.2.1.2 Impact on Voltage drop

The second parameter to be investigated is voltage drop at bus 5 from LV side with 200kW EVCS installed. Figure 5.5 shows how bus 5 performed well with EVCS type 1in terms of voltage drop with peak value of 583.1 V even though its THD level exceeds the limit. This highlights what has been said in the previous section that a comprehensive evaluation should be implemented before approving installation of specific charging station type. Type 2 experience approximately a drop of 9.8 V below the nominal peak value as in Figure 5.6. the largest drop in bus 5 took place when type 3 is integrated and the peak value drops down to 565.2 V as demonstrated in Figure 5.7 with voltage drop of 21.7 V. nevertheless, all the resulted peak values are still within Kahramaa standard limit of allowable 6% voltage drop giving a chance to install more charging stations.

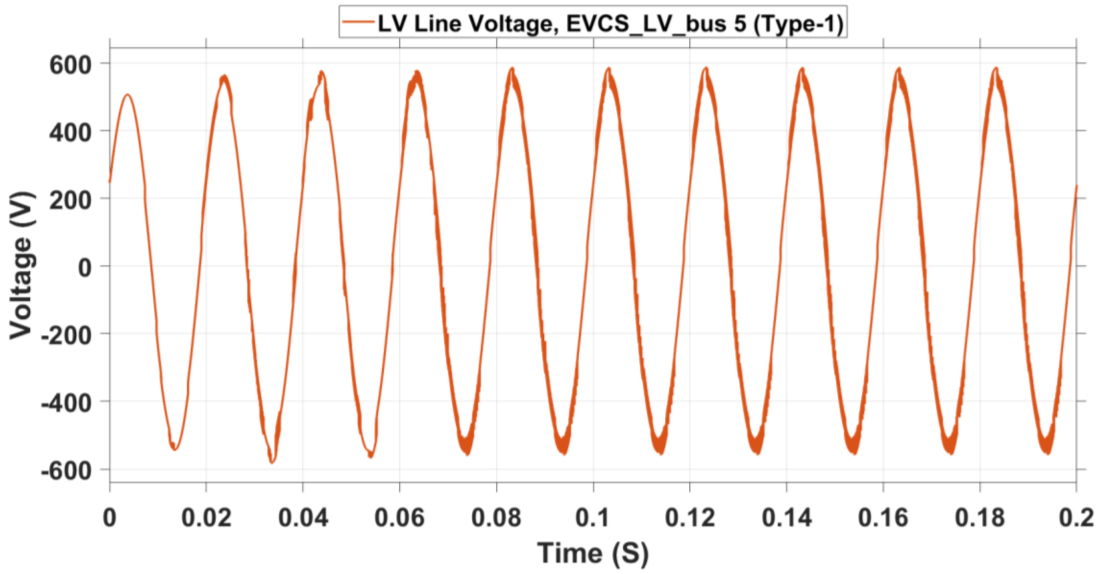

Figure 5.5. Line voltage at EVCS_LV_bus 5 (type-1).

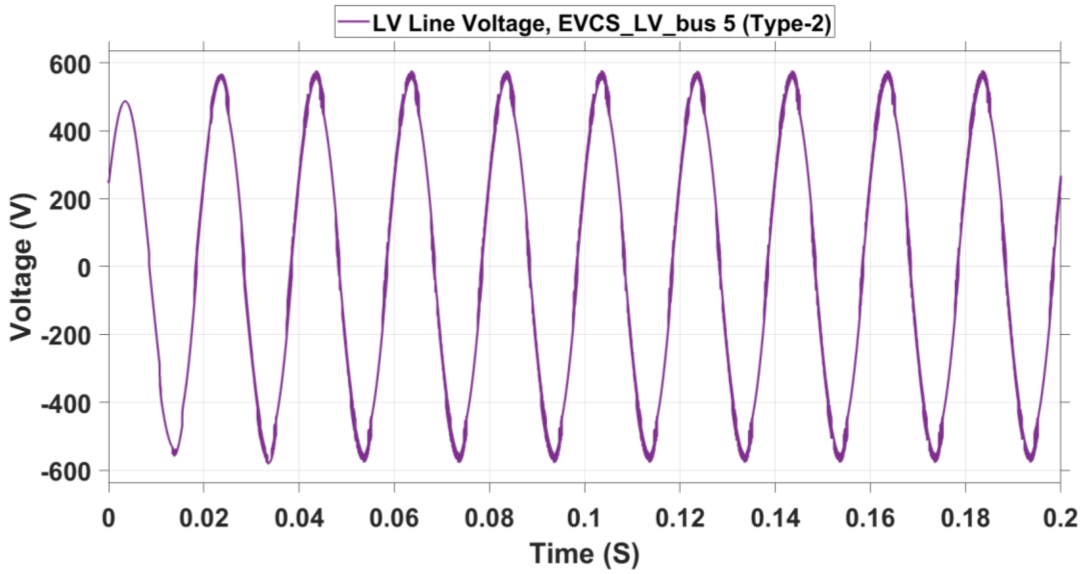

Figure 5.6. Line voltage at EVCS_LV_bus 5 (type-2).

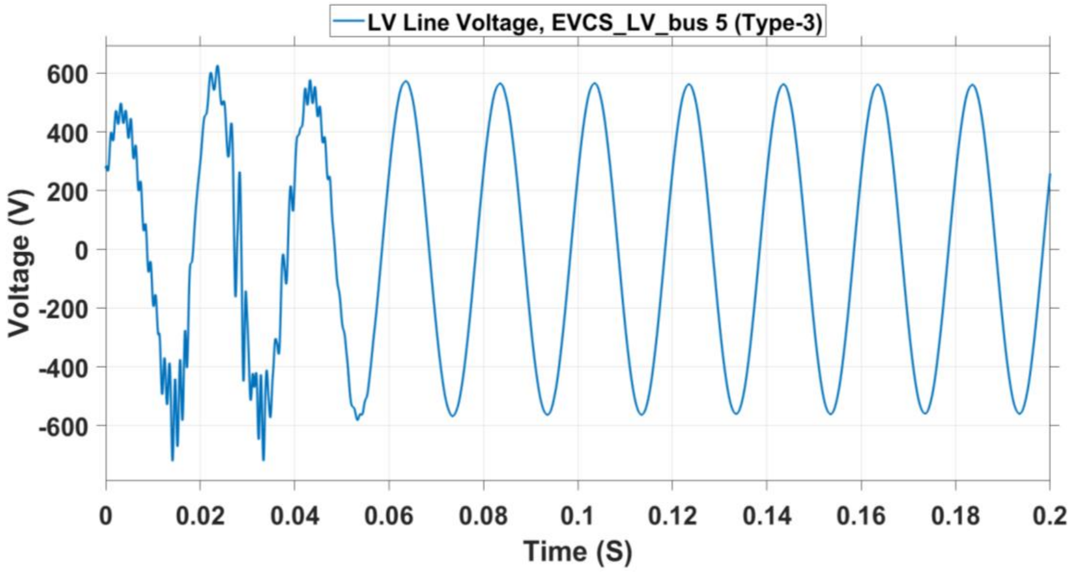

Figure 5.7. Line voltage at EVCS_LV_bus 5 (type-3).

5.2.1.3 Impact on line losses

From power perspective, table 5.1 gives summary of feeder 4-5 for each type of EVCS when they connect separately. Type 1 experiences line losses of 1.613 kW approximately with increase of 1.57kW above the key model value. Moreover, Type 3 shows 1.054 kW losses and it rise by amount of 1.01 kW while type 2 is the least among all three with 0.6698 kW and an increase by 0.62 kW. looking at feeder performance from system losses point view, it can be seen that type 1 demonstrates the largest losses with 2.83% of the total losses while type 2 and 3 result in 1.13% and 1.82 respectively.

Table 5.1. Feeder 4-5 Line Losses with Penetration of Single Type EVCSs

Type	Line Losses (kw)	Increase (kW)	% of Total Losses
1	1.613	1.56919	2.83
2	0.6698	0.62599	1.13
3	1.054	1.01019	1.82

5.2.2 EVCS penetration impact of different types on low voltage feeder

Second part of scenario 1 of feeder investigation process is to integrate EVCS of different types and evaluate system behavior again regarding THD level, voltage drop and feeder losses. Figure 5.8 shows feeder 4-5 and the connection of EVCS type 1 and 2 where the other combinations are typical.

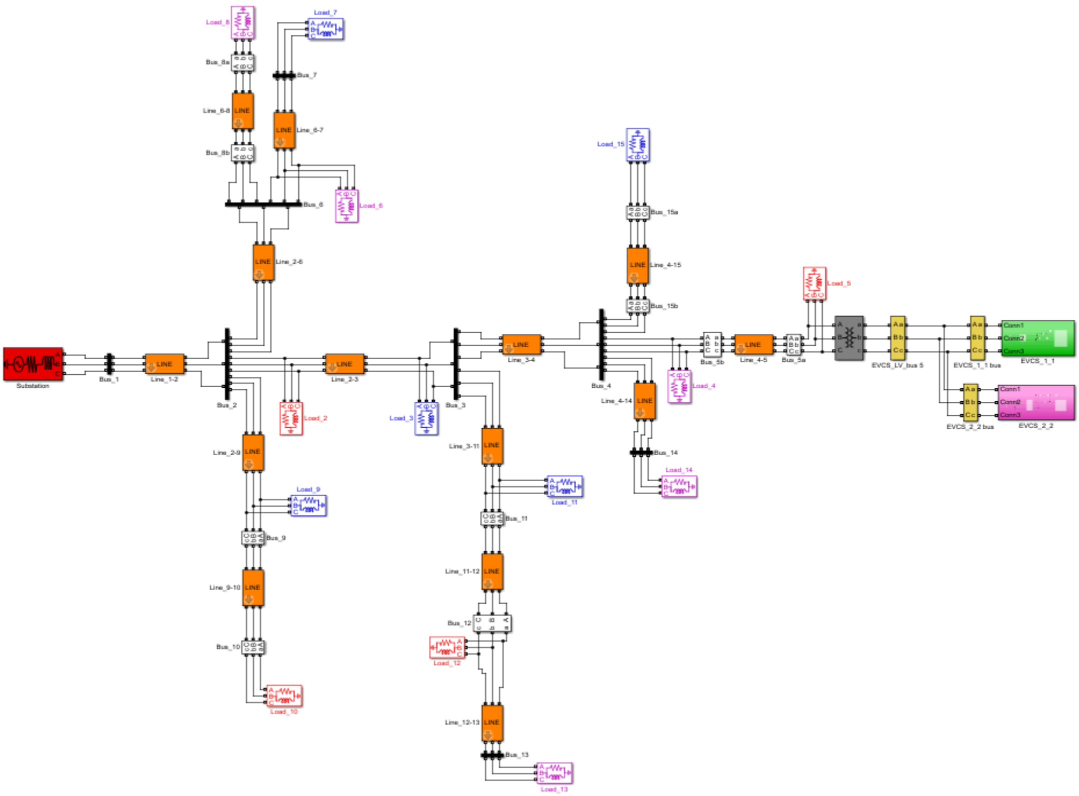

Figure 5.8. EVCS-connected LV feeder (type-1 & 2).

5.2.2.1 Impact on THD level

From Figure 5.9, it can be seen that a combination between EVCS type 1 and 2 raises THD level to 4% and the main contribution is resulting from type 1 due to its inherit harmonic generating behavior. On the other hand, integration of type 1 and 3 generates THD level of 2.75% as it shown in Figure 5.10.

However, type 2 and 3 combination results in the least THD level with 1.35% only in comparison to the other arrangements and Figure 5.11 demonstrates the results. These finding are in accordance with the individual nature of each type and from the previous discussion in chapter 4 and if three types to be put in order in terms of THD generation, type 1 will be placed first and type 3 is the least THD generating source.

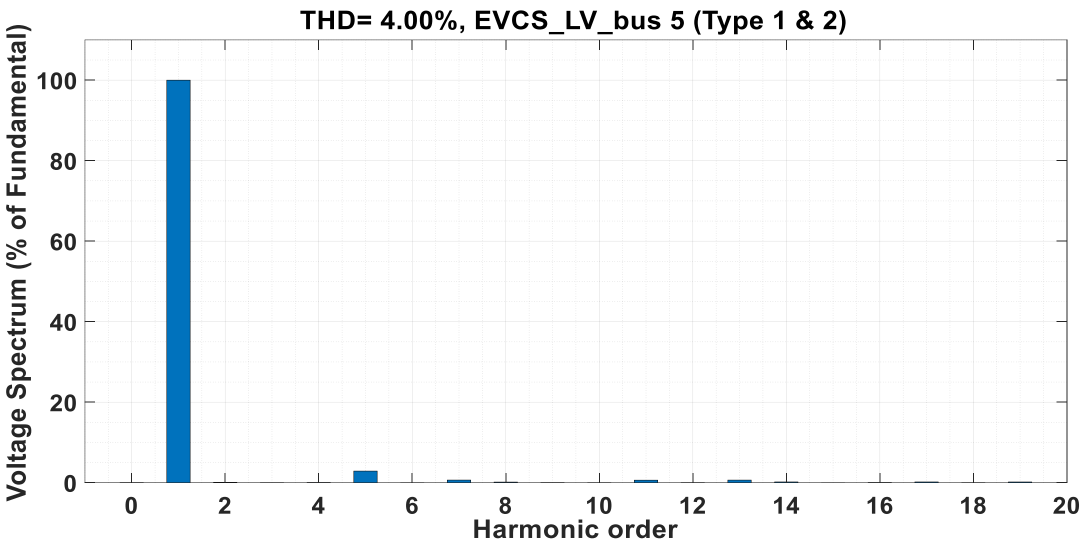

Figure 5.9. THD level at EVCS_LV_bus 5 (type-1 & 2).

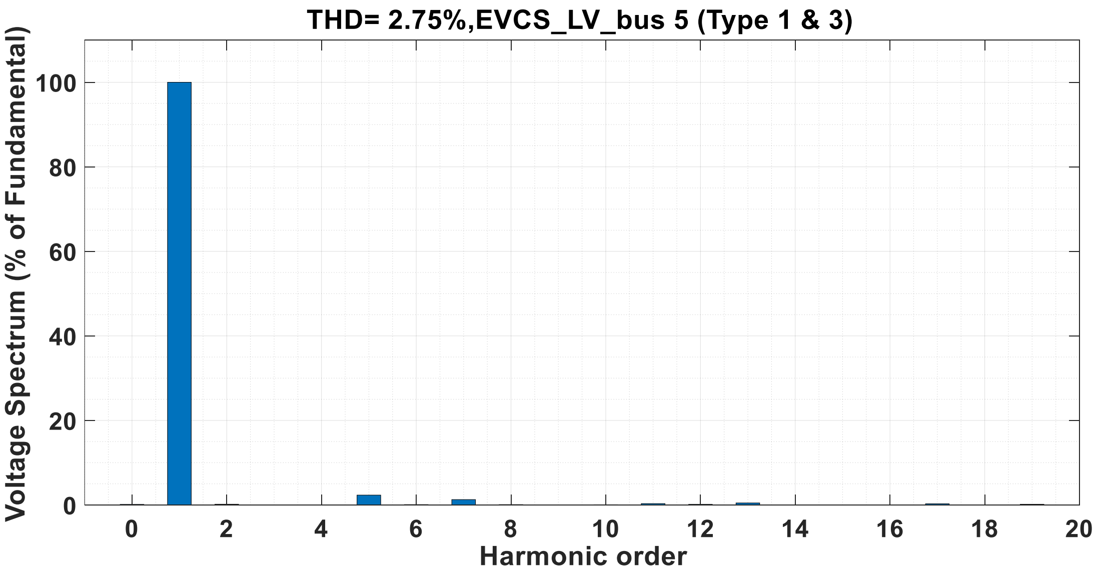

Figure 5.10. THD level at EVCS_LV_bus 5 (type-1 & 3).

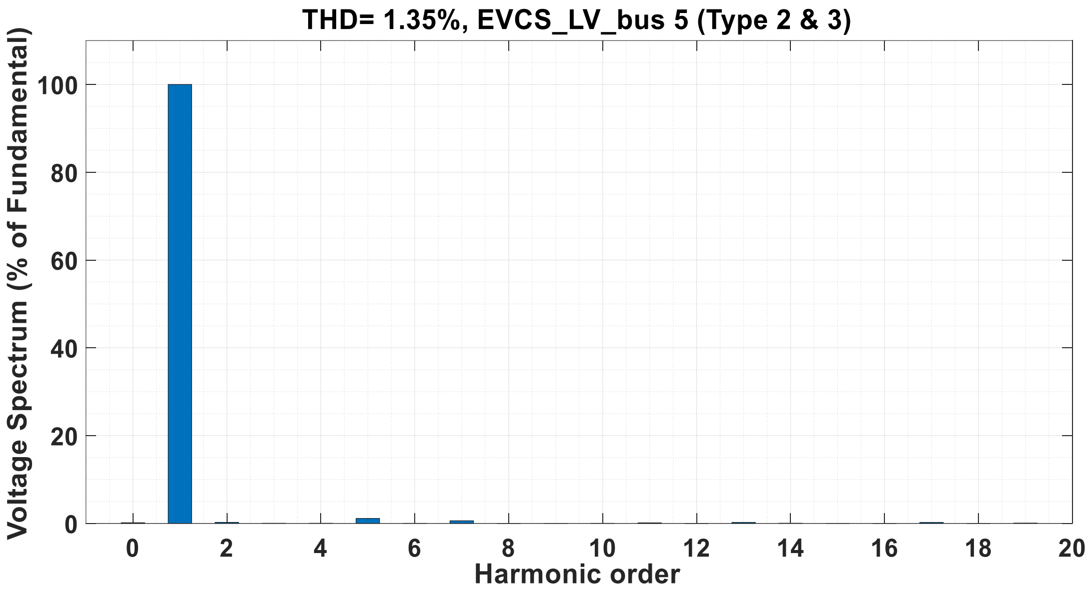

Figure 5.11. THD level at EVCS_LV_bus 5 (type-2 & 3).

5.2.2.2 Impact on Voltage drop

Voltage drop at bus 5 has not varied greatly with presence of different EVCS combinations. Connecting type 1 and 2 results in 571.3 V with drop of 15.6 V as it shown in Figure 5.12 while type 2 and 3 experiences a drop of 16V where the peak value reaches 570.9 V as demonstrated in Figure 5.14. However, in Figure 5.13 The least voltage drop is found with type 1 and 3 integrations where nominal peak value drop down to 577.2 V.

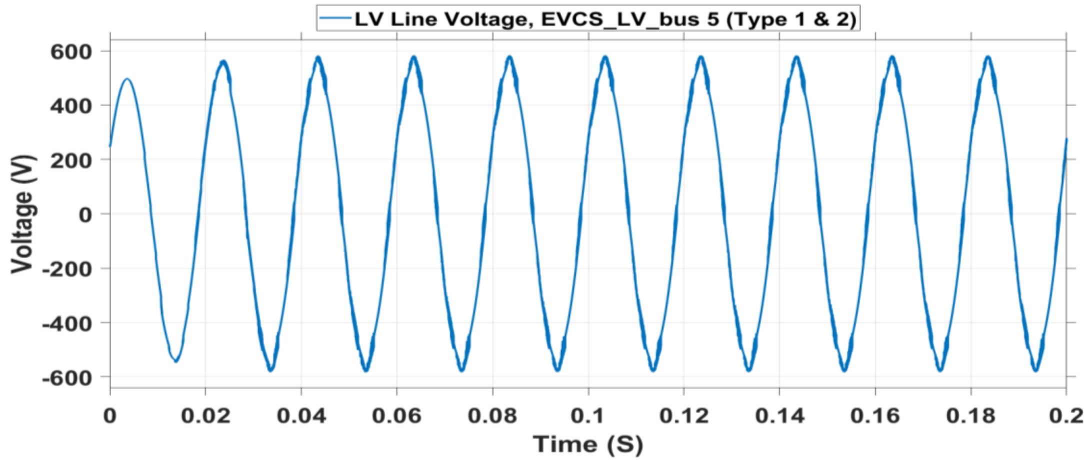

Figure 5.12. Line voltage at EVCS_LV_bus 5 (type-1 & 2).

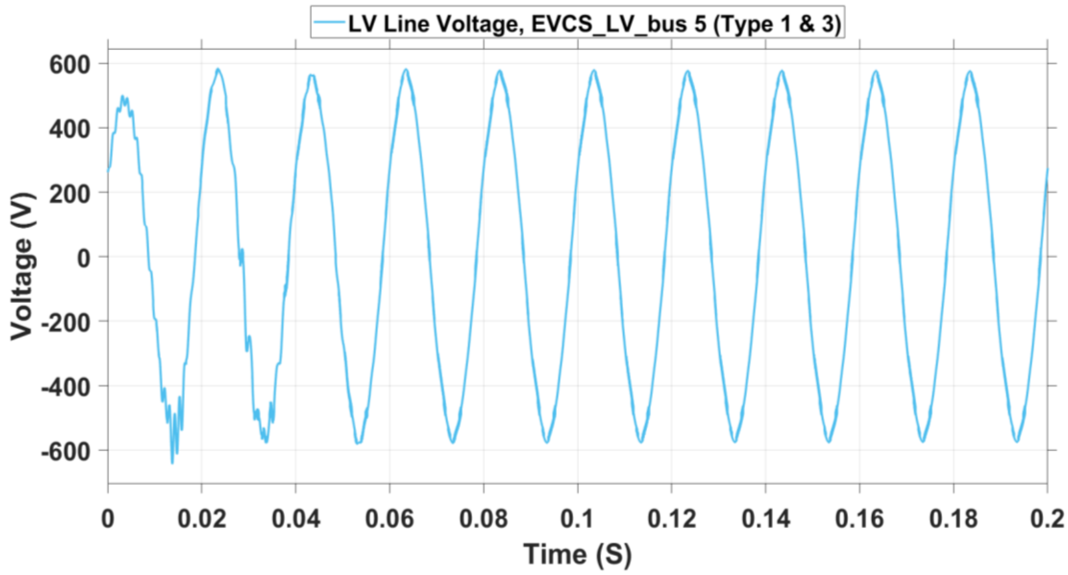

Figure 5.13. Line voltage at EVCS_LV_bus 5 (type-1 & 3).

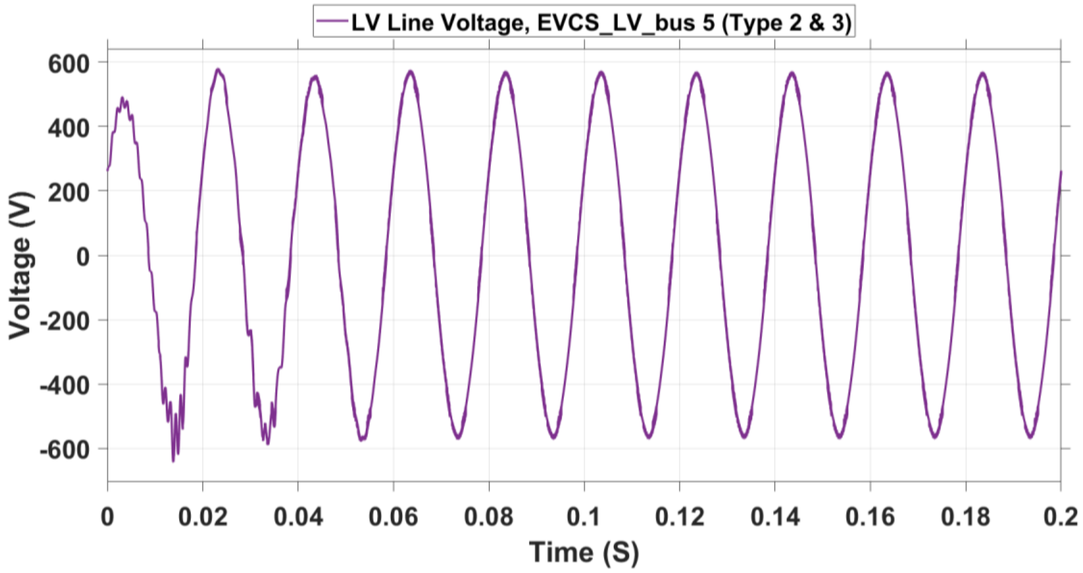

Figure 5.14. Line voltage at EVCS_LV_bus 5 (type-2 & 3).

5.2.2.3 Impact on line losses

For line losses, it can be seen from table 5.2 that the increase in losses varies from 0.23 kW for type 1 and 3 grouping to 0.72 kW in the arrangement of type 2 and 3. The largest loss took place when type 2 and 3 is connected with 1.31% of system total loss.

Table 5.2. Line Losses with Penetration of Multi Types EVCSs

Type	Line Losses (kw)	Increase (kW)	% of Total Losses
1 and 2	0.4623	0.41849	0.75
1 and 3	0.2792	0.23539	0.42
2 and 3	0.7726	0.72879	1.31

In summary, system behavior for both integrations of one type or different types shows various responses. For example, when EVCS type 1 and 2 are combined together, THD level drops down to 4% in comparison to type one only which went beyond the standard limit. Moreover, type 3 THD level is considered as the least among the other types but when it combined with type 1 and 2, THD increases to 2.75% and 1.35% respectively. On the other hand, for the voltage drop, all the tested scenarios performed well and operated within the acceptable range with slight different from one arrangement to another. The optimal choice is the integration of type 1 only where it scores 583.1V peak value while the worst case scenario occurred when with type 3 where the voltage drops reaches 21.7V. from line losses perspective, it ranges from 2.83% with insertion of type 1 only to 0.42% where type 1 and 3 are combined. Table 5.3 summarizes the results for scenario 1.

Table 5.3. Results Summary for Scenario 1

Type	THD	Line Peak Voltage (V)	% of Total Losses
1	5.57	583.1	2.83
2	2.58	577.1	1.13
3	0.5	565.2	1.82
1 and 2	4	571.3	0.75
1 and 3	2.75	577.2	0.42
2 and 3	1.35	570.9	1.31

5.3 Grid-connected EVCS impact on 415V Feeder with Renewable Energy Source

In this section, photovoltaic (PV) source is simulated using MATLAB/SIMULINK software and the main purpose is to integrate this renewable energy source into EVCS-connected grid in order to compare system performance the results that had been discussed in the previous section.

5.3.1 Simulation of 415V, 100kW PV array

Firstly, the PV system is simulated using the parameters listed in table 5.4 where the required output power is 100 kW at 415 V in order to match the rated power of EV charging station and system voltage. With 1000w/m^2 irradiance and 25 deg.C, the system generates 600 VDC with open circuit voltage of 36.3 V as standard value for this model. Simulink model is shown in Figure 5.15 where the PV is connected to boost converter with MPPT algorithm in order to maximize the output power. The resulted 600 VDC from boost converter is connected to three phase inverter where PMW technique is applied to generate the required 415 V grid voltage which by then is connected to LCL filter before it is integrated into the system. For details on PV modelling and converter simulation, the interested reader may refer to [68].

Table 5.4. PV System Parameters

Parameter	Value
Irradiance	1000 W/m^2
Temperature	25 deg.C
Parallel String	47
Series connected modules per String	10
Open Circuit Voltage (V_{OC})	36.3V
DC voltage	600V
Output three phase voltage	415V, Line-Line RMS
Output Power	100kW

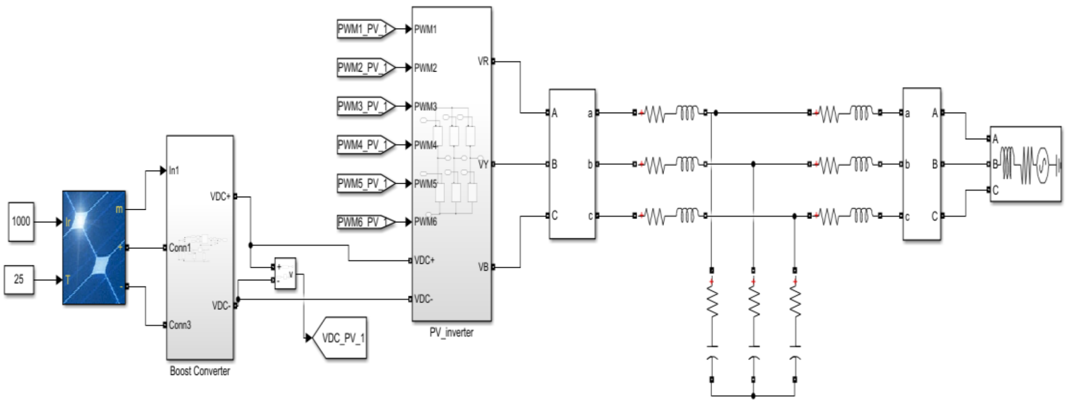

Figure 5.15. PV system simulink model.

The output DC voltage from the converter is shown in Figure 5.16 where it can be seen that the signal experiences transient period with overshooting percentage more than 40%. Moreover, the settling time is considered long with nearly 0.04s before the signal settles down to its final value. On the other hand, in the steady state period, the waveform shows non-zero ripples although steady state error is almost zero.

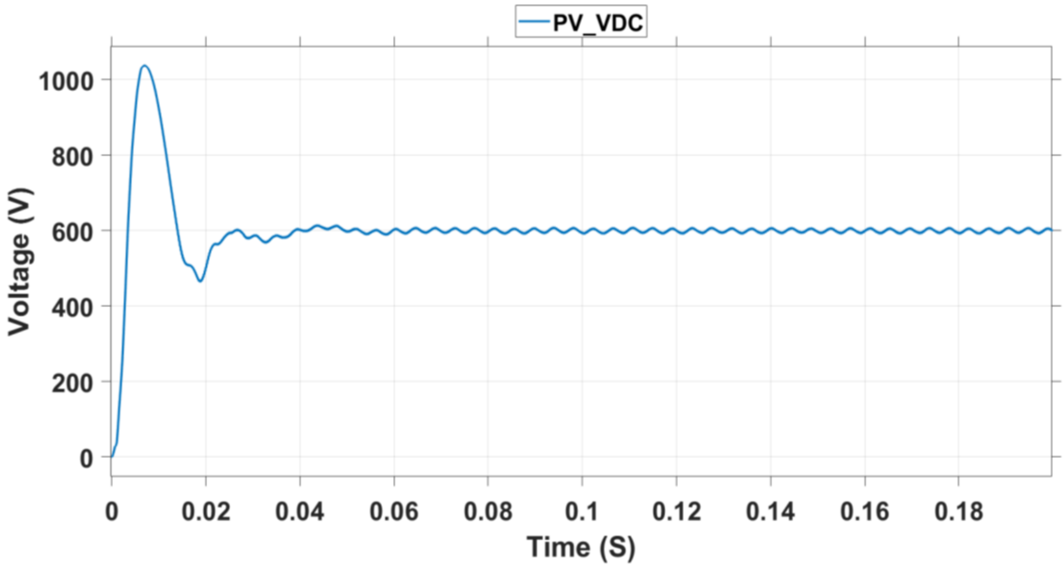

Figure 5.16. PV boost converter output voltage.

Figure 5.17 demonstrates the output phase voltage with peak value is 338.84 V corresponding to grid nominal peak value of 586.9 V. in general, the signal is performed smoothly without any considerable distortion or severe overshooting in transient period.

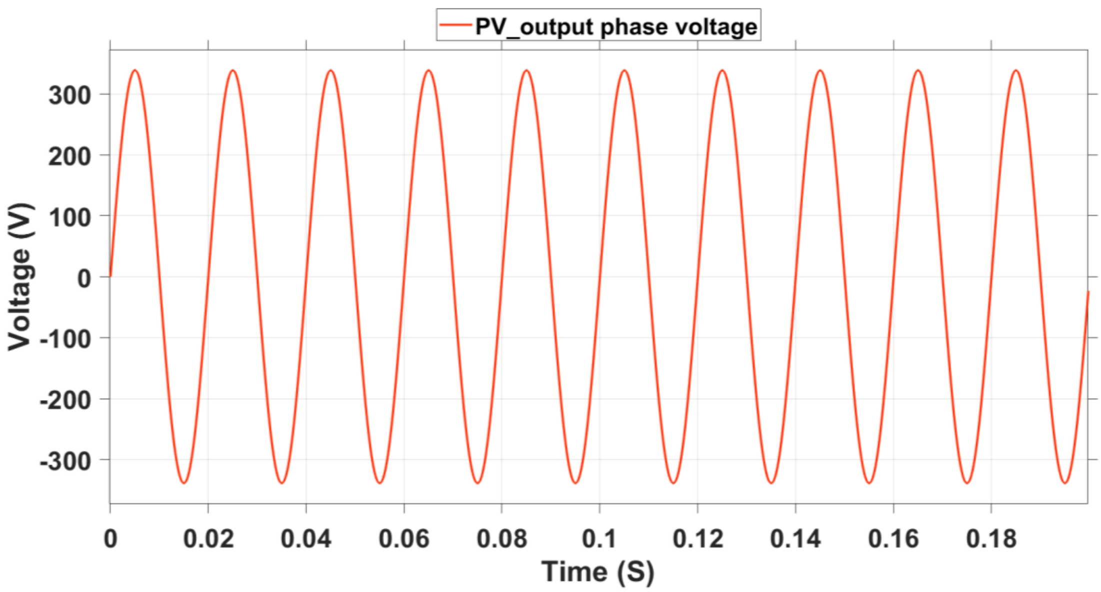

Figure 5.17. PV inverter output phase voltage.

Finally, the output power is given in Figure 5.18 where the signal reaches its final value of 100 kW at approximately 0.04s. in the time range from 0 to 0.02, signal went beyond 200 kW which may effected by the DC voltage overshooting. However, the waveform in steady state period demonstrates smooth response with almost zero ripples.

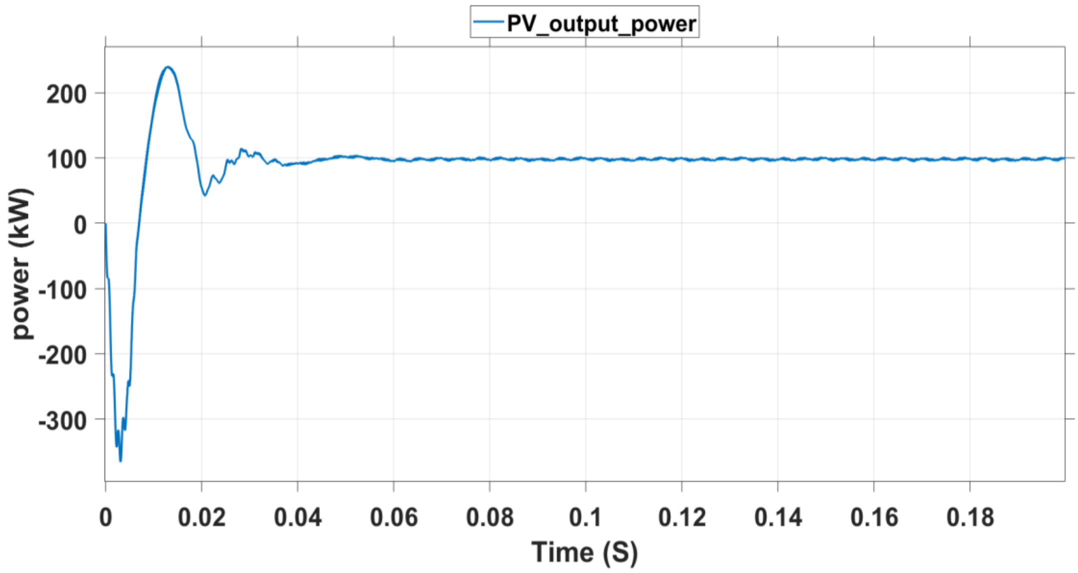

Figure 5.18. PV output power.

After the brief discussion of the PV system, next section, it will be integrated into the distribution system with presence of EVCS and the system performance to be evaluated again in terms of THD level, voltage drop and power losses taking feeder 4-5 as a case study for that.

5.3.2 Impact EVCS of one type on low voltage feeder with integration of PV

The first scenario that has been investigated is the integration of renewable energy source (RES) with EVCS of one type into the grid. Figure 5.19 shows three phase line diagram where RES and two EVCSs of type 1 is connected at bus 5 at LV side of 11kV/415V, 1600 kVA transformer.

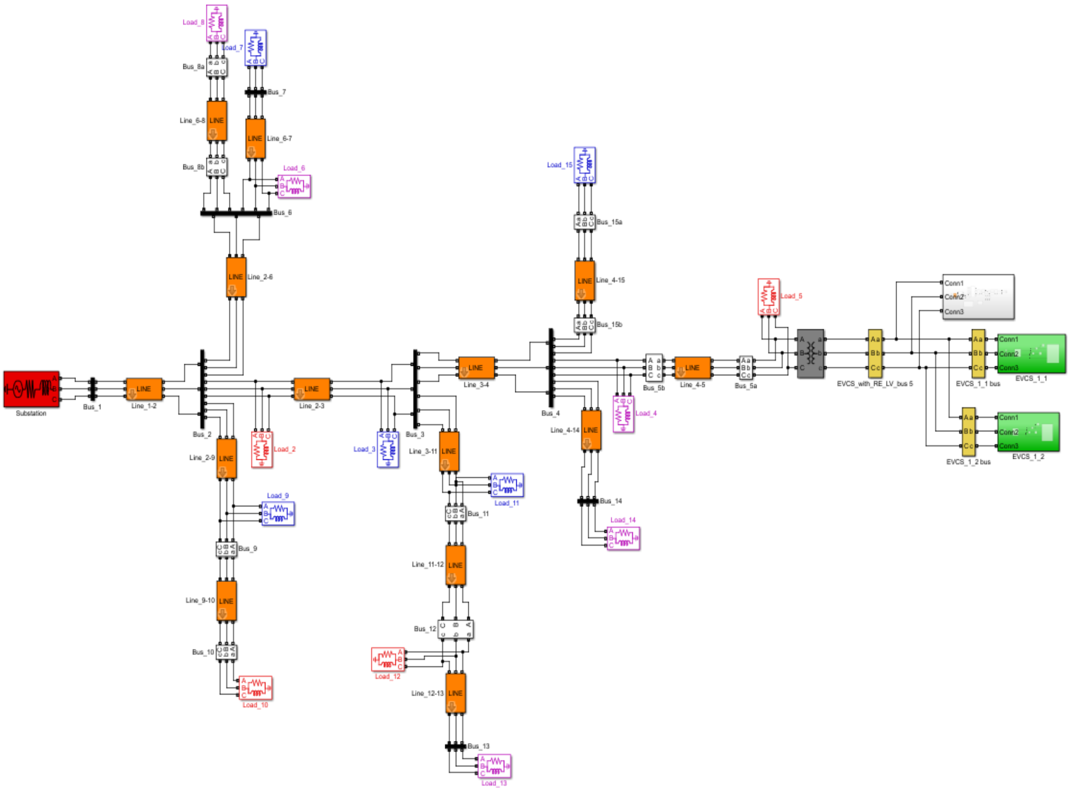

Figure 5.19. EVCS-connected LV feeder with RES integration (type-1).

5.3.2.1 Impact on THD level

With integration of RES, THD level changes and this change varies from scenario to another. Figure 5.20 shows voltage spectrum of bus 5 with combination of RES and EVCS type 1 and it can be seen that THD level drops from 5.57% to 4.68% bringing back this scenario to play within standard limit. In Figure 5.21, EVCS type 2 expresses 2.7% with presence of RES while type 3 have THD value of 0.24% as in Figure 5.22 instead of 0.5% in the absence of PV source.

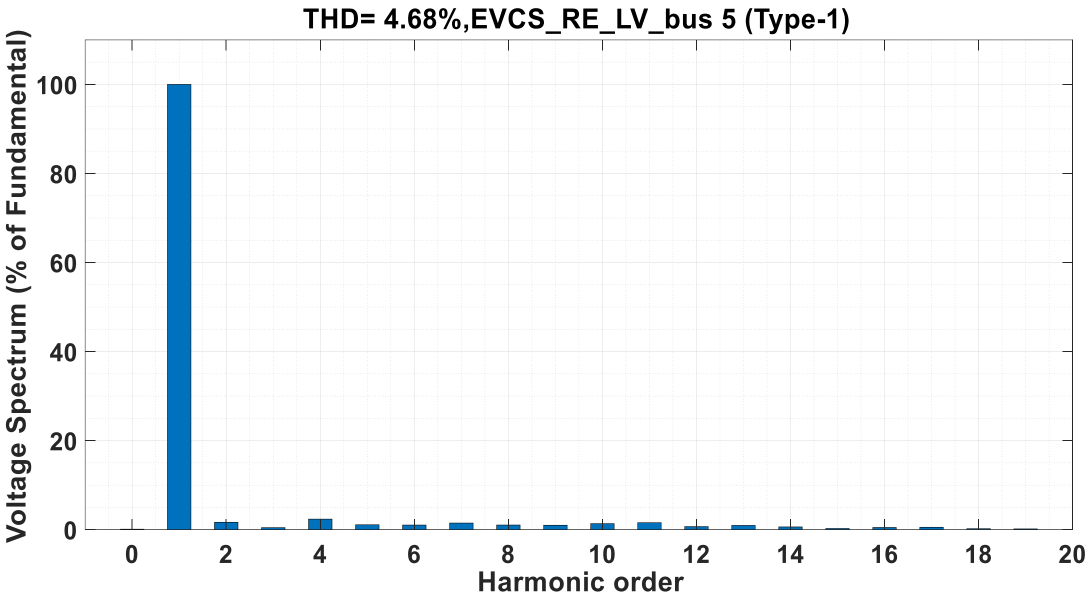

Figure 5.20. THD level at EVCS_LV_bus 5 with RES integration (type-1).

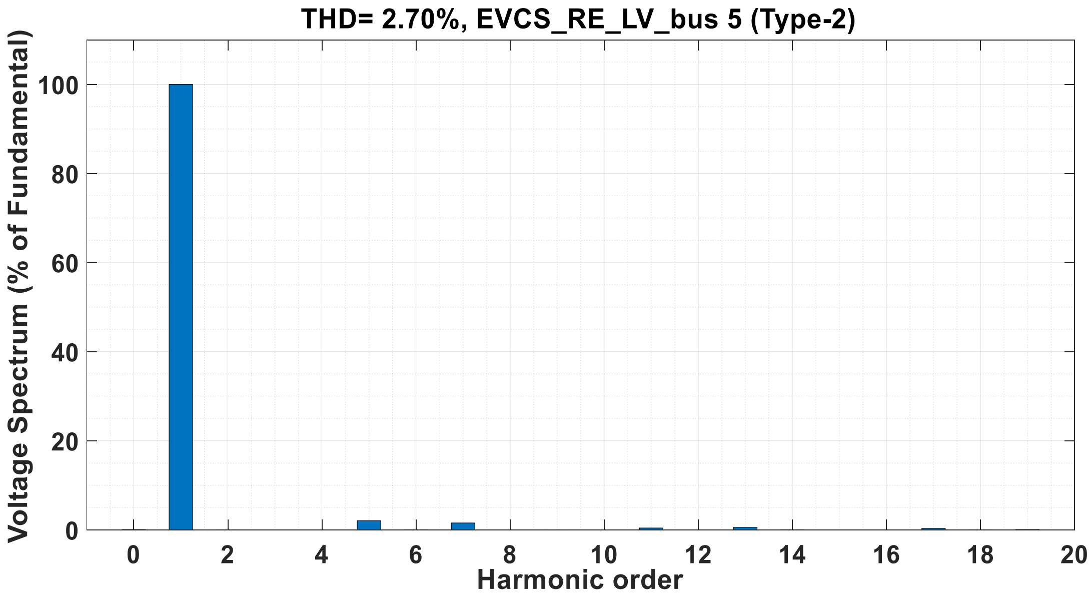

Figure 5.21. THD level at EVCS_LV_bus 5 with RES integration (type-2).

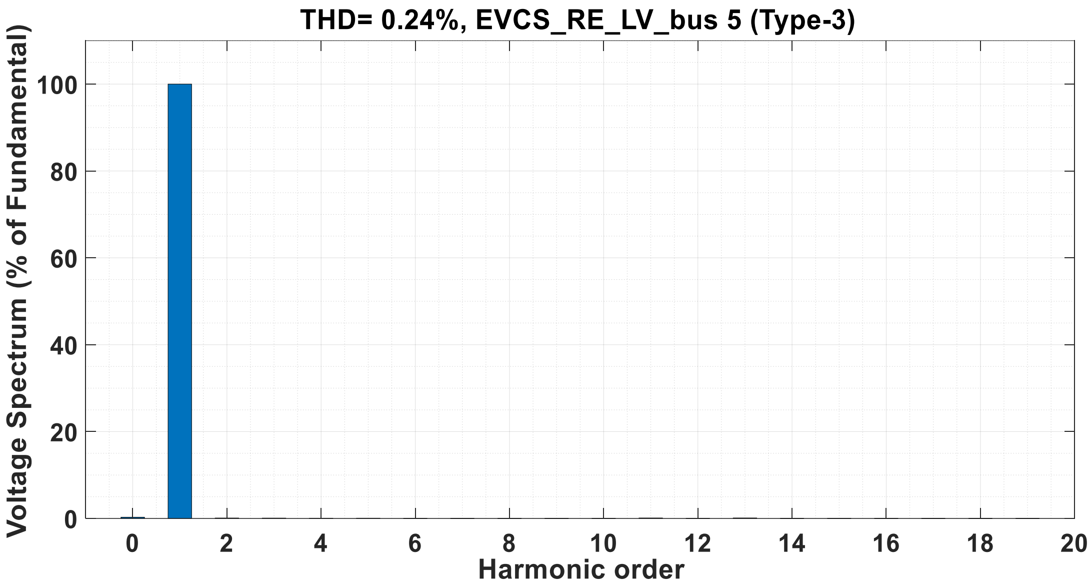

Figure 5.22. THD level at EVCS_LV_bus 5 with RES integration (type-3).

5.3.2.2 Impact on Voltage drop

In terms of voltage drop, type 1 results in 581.7 peak value as in Figure 5.23 which is relatively the same value before the integration of RES. Moreover, type 2 and 3 show peak values of 577.9 V and 567 V and the results are given in Figure 5.24 and 5.25 respectively. It may be noticed that from voltage drop perspective, all the types operate within Kahramaa standard limit of 6%. The voltage waveform still suffers from highly harmonic contamination in the transient period as it is shown previously and the major justification refers to the nature of the control mechanism which beyond the scope of this study.

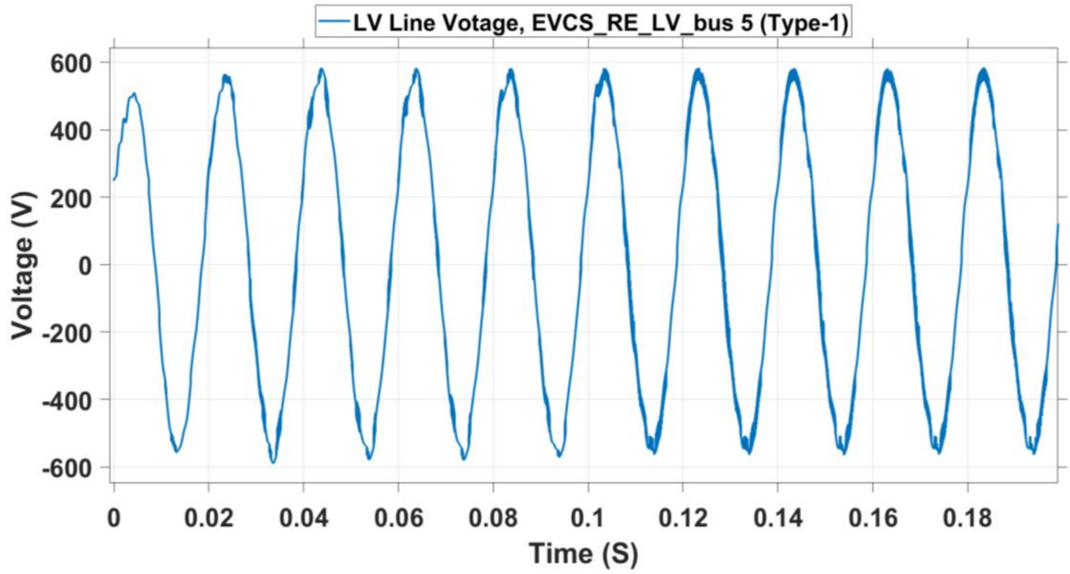

Figure 5.23. Line voltage at EVCS_LV_bus 5 with RES integration (type-1).

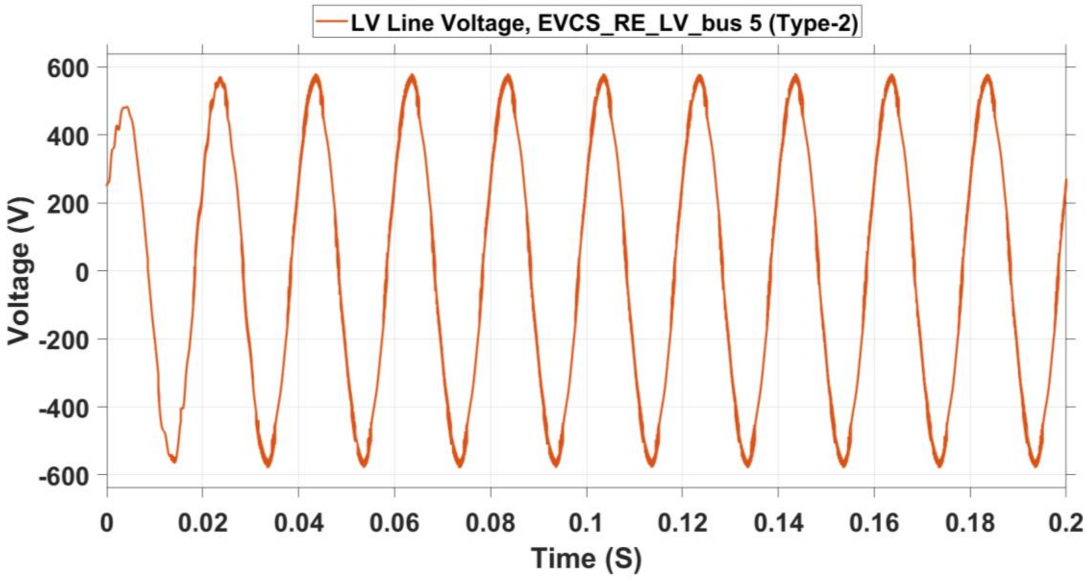

Figure 5.24. Line voltage at EVCS_LV_bus 5 with RES integration (type-2).

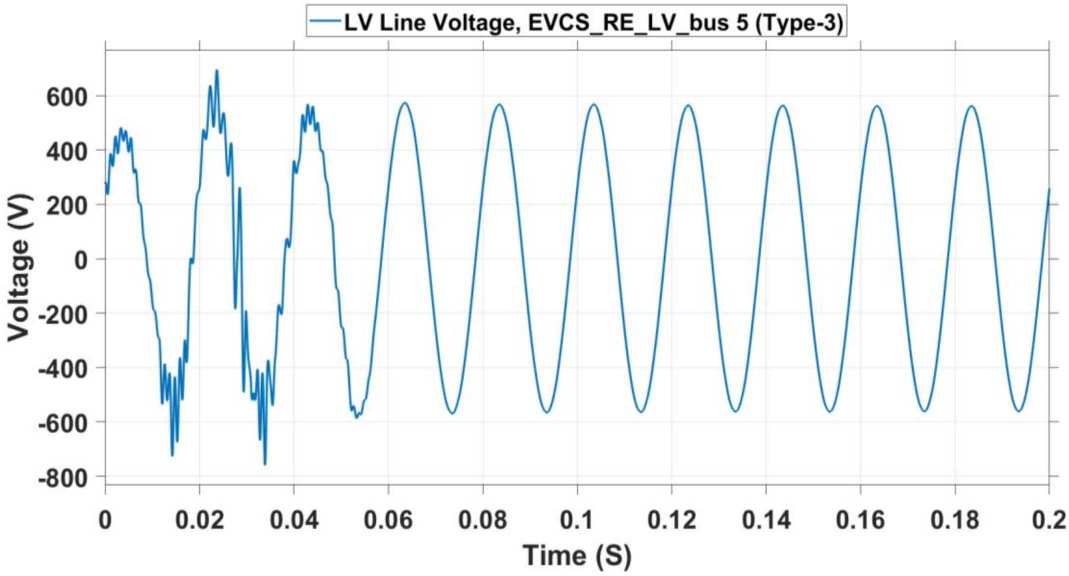

Figure 5.25. Line voltage at EVCS_LV_bus 5 with RES integration (type-3).

5.3.2.3 Impact on line losses

With presence of PV source, feeder 4-5 experiences losses that vary from 0.5155kW with integration of type 1 to 0.978 kW with the connection of type 3. The highest rise occurs with EVCS type 3 where the line losses increase reach 0.93 kW as 1.69% of system total losses. on the other side, an integration of RES and EVCS type 2 gives the minimum losses with increase of 0.2 kW and 0.36%. table 5.5 summarizes the results.

Table 5.5. Line Losses with Penetration of Single Type EVCSs & RES

Type	Line Losses (kw)	Increase (kW)	% of Total Losses
1	0.5155	0.47169	0.85
2	0.2452	0.20139	0.36
3	0.9784	0.93459	1.69

5.3.3 Impact EVCS of different types on low voltage feeder with integration of PV

In this section, different EVCS types have been integrated with RES into bus 5 which is supplied from feeder 4-5. Figure 5.26 shows the connection of EVCS type 1 and 2 with presence of PV source and the other two combinations are in typical arrangement.

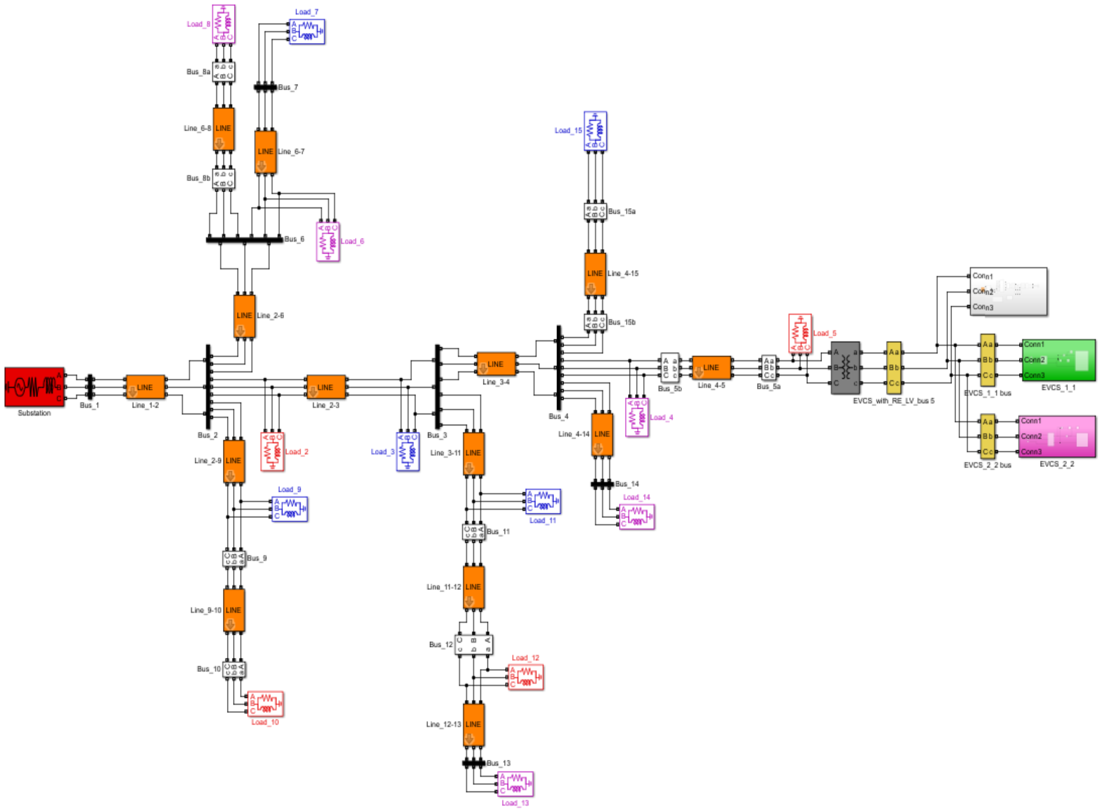

Figure 5.26. EVCS-connected LV feeder with RES integration (type-1 & 2).

5.3.3.1 Impact on THD level

From THD point view, the results from the combination of RES and various types of EVCS show that all the scenarios are working within the international standard limit of 5%. For instance, Figure 5.27 gives 3.31% as THD level value for combination of EVCS type 1 and 2 with presence of PV source. Moreover, Figure 5.28 and 5.29 demonstrate the integration of type 3 with 1 and 2 respectively. The minimum THD level is achieved when type 2 and 3 are combined with 1.33% and this result aligned with the fact that type 3 is the least THD generator and hence any combination with it will drop down the value.

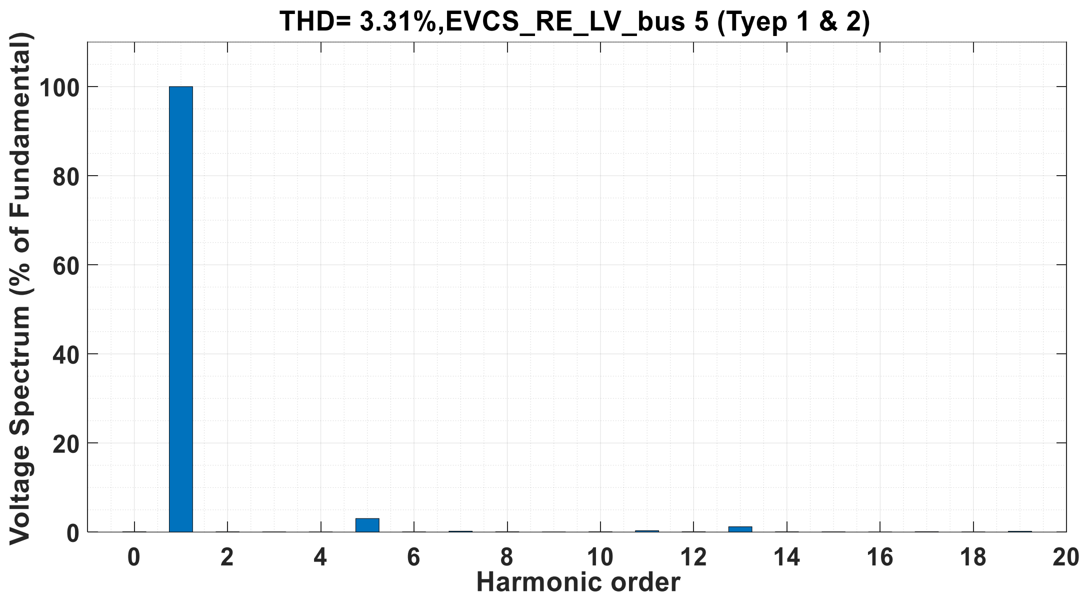

Figure 5.27. THD level at EVCS_LV_bus 5 with RES integration (type-1 & 2).

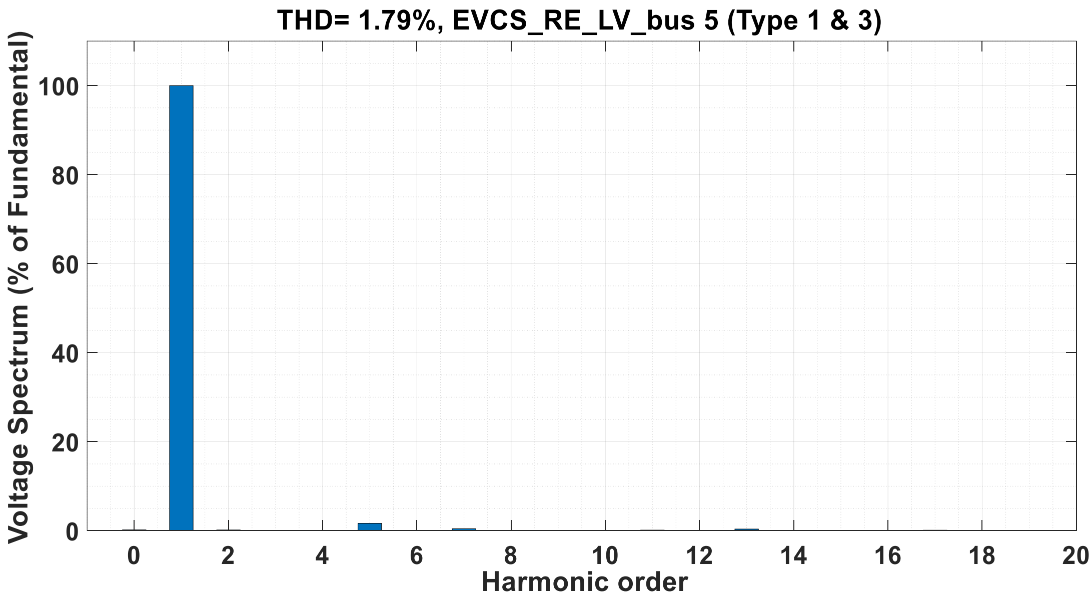

Figure 5.28. THD level at EVCS_LV_bus 5 with RES integration (type-1 & 3).

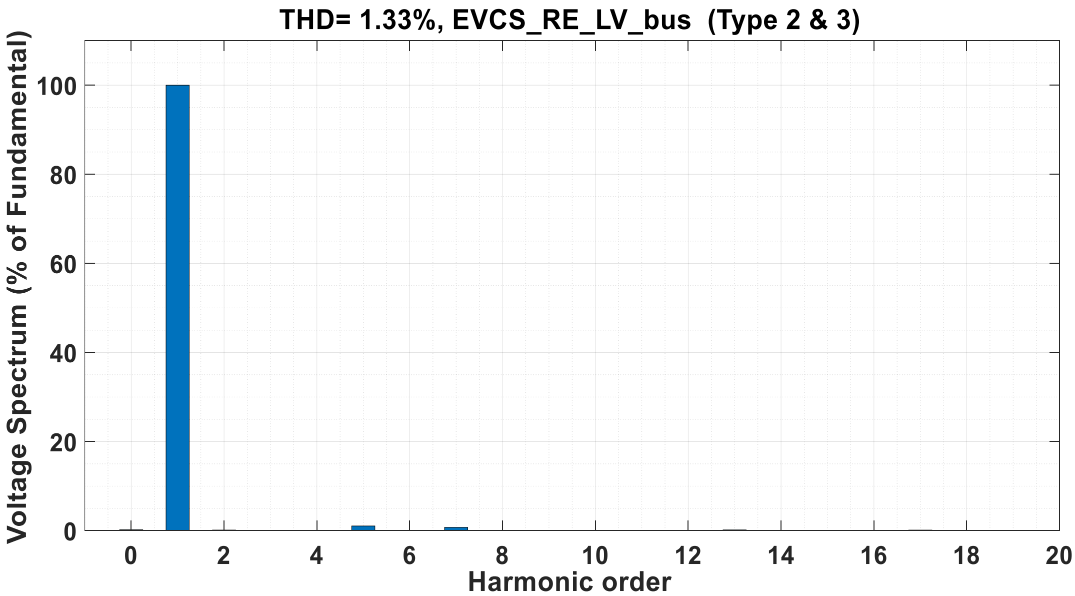

Figure 5.29. THD level at EVCS_LV_bus 5 with RES integration (type-2 & 3).

5.3.3.2 Impact on Voltage drop

Voltage drop at bus 5 shows that the system performs good when different EVCS are connected together. In Figure 5.30, with type 1 and 2 integrated, line voltage drops down to 581.3 V with drop of 5.6 V while in Figure 5.32, bus 5 suffers the highest drop with peak value of 572.7 V and drop of 14.2 V when type 2 and 3 are combined. Furthermore, a combination of type 1 and 3 results in 577.5 V peak value with drop of 9.4 V as it is shown in Figure 5.31. All the values are within Kahramaa standard limit with different operating margins.

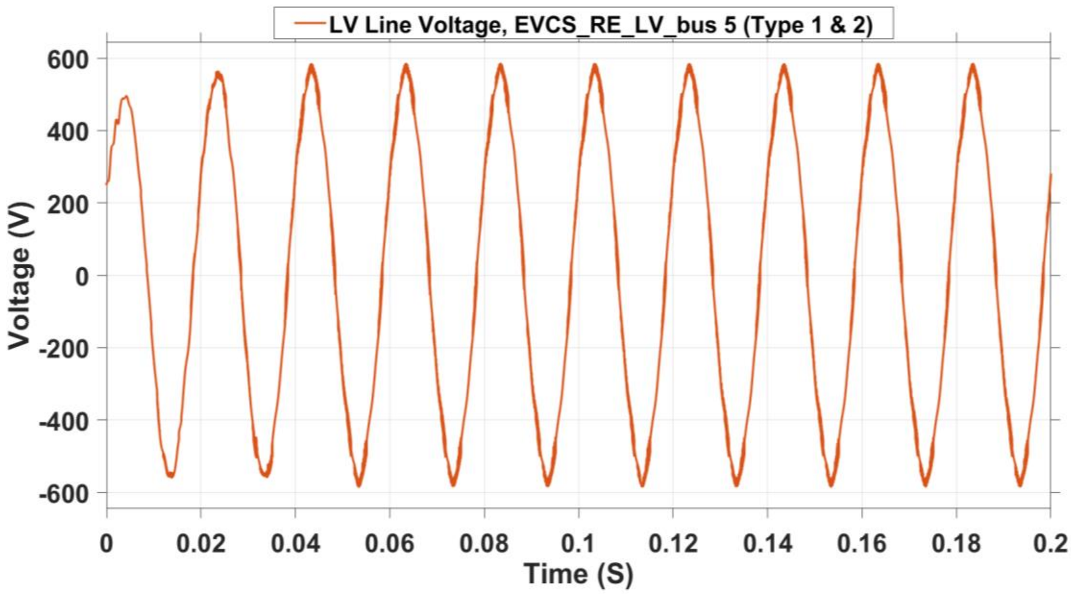

Figure 5.30. Line voltage at EVCS_LV_bus 5 with RES integration (type-1 & 2).

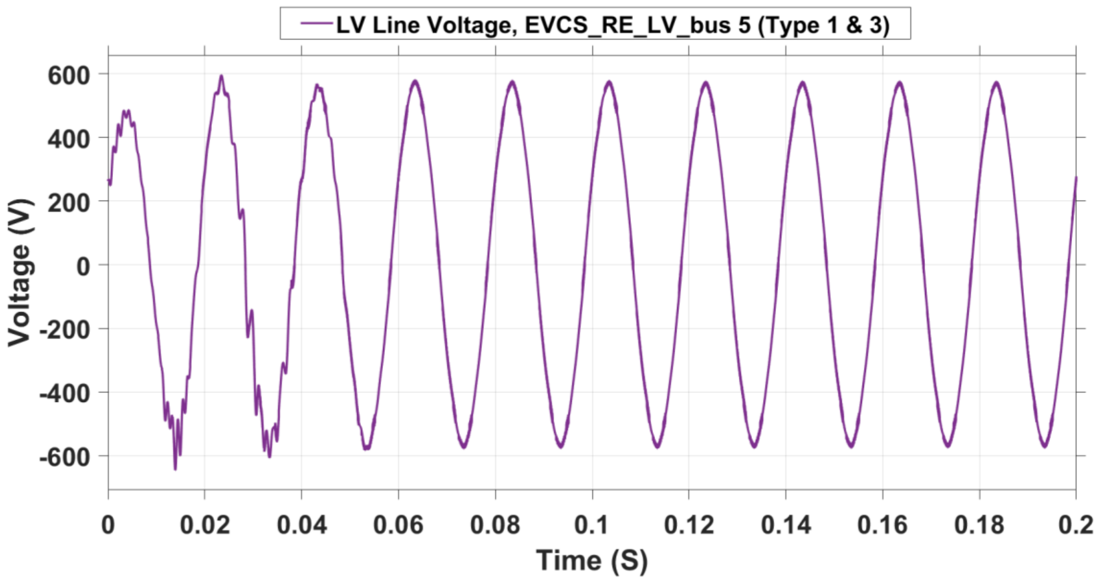

Figure 5.31. Line voltage at EVCS_LV_bus 5 with RES integration (type-1 & 3).

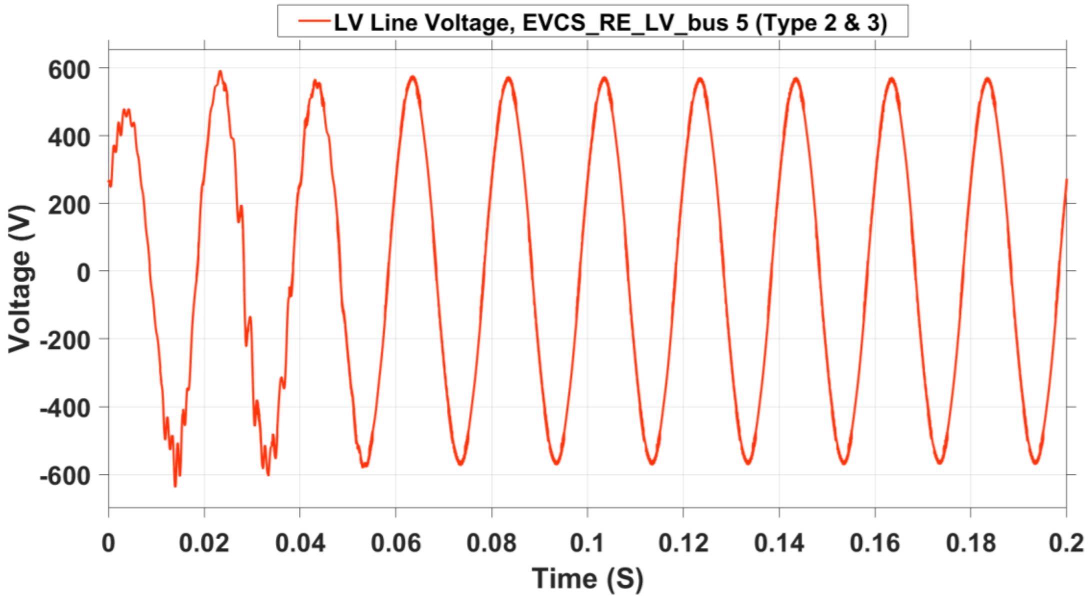

Figure 5.32. Line voltage at EVCS_LV_bus 5 with RES integration (type-2 & 3).

5.3.3.3 Impact on line losses

With presence of RES, the various combination demonstrates acceptable performance from line losses perspective, table 5.6 shows how the system reacts when various EVCS are connected with PV source at the same bus. the minimum loss is 0.09 kW with increase of approximately 0.048 kW and this occurs when type 1 and 2 interconnected. However, the combination of type 1 and 3 shows the maximum loss with increase of 0.157 kW. from system total losses, the three combination vary from 0.09% of the total losses to 0.28% which indicates that the system performs well in these scenarios.

Table 5.6. Line Losses with Penetration of Multi Type EVCSs & RES

Type	Line Losses (kw)	Increase (kW)	% of Total Losses
1 and 2	0.0924	0.04859	0.09
1 and 3	0.201	0.15719	0.28
2 and 3	0.1654	0.12159	0.22

Table 5.7 summarize the results of RES penetration impact on EVCS-connected distribution system.

From THD perspective, it is noticed that scenarios where single type is integrated, the THD level decreases in general. For instance, before the insertion of PV, type 1 has THD value of 5.57% which exceeds the limit. However, when PV system is penetrated, it drops down to 4.68% making bus voltage to operate within the limit again. On the other, hand, type 2 THD level increases from 2.58% to 2.7% once the PV is penetrated which indicating that PV system inject harmonic into the system and it is considered normal because the renewable energy source is THD generator by itself due to its non-linearity nature.

Furthermore, voltage drop has not expressed significant change due to insertion of PV system with both single type or multi types scenarios. Looking at power losses results, it can be noticed that a crucial shift occurred once RES is penetrated. For instance, the tested feeder with type 1 experiences 2.83% losses while this value drops down significantly to 0.85% when PV system is integrated.

Table 5.7. Results Summary for Scenario 2

Type	THD	Line Peak Voltage (V)	% of Total Losses
1	4.68	581.7	0.85
2	2.7	577.9	0.36
3	0.24	567	1.69
1 and 2	3.31	581.3	0.09
1 and 3	1.79	577.5	0.28
2 and 3	1.33	572.7	0.22

5.4 Summary

In this chapter, low voltage EVCS-connected feeder is investigated in two case scenarios; one without PV system and the other when it is integrated. Firstly, EVCS single type is considered and the results show improvement in the presence of PV system. Secondly, a combination between different EVCS is connected to the feeder and is had been seen that the system performs better than single type mode.

From general point, the penetration of PV source improved system performance and hence can be considered as alternative solution to the scenarios where the parameters violated Kahramaa standards due heavy existing loads on the tested feeders or in the remote areas where the cables travel long distance.

In next chapter, a comparison between 11kV and 415V feeders will be investigated in terms of THD level

Chapter 6: Comparison of EVCS Impact on 11kv and 415V Feeders THD Level

6.1 Introduction

Total harmonic distortion is one of the main effected distribution network parameters by EVCS penetration due to non-linearity nature of the power converters consisting charging station. For that, it is highly important to investigate the EVCS impact on distribution network in terms of THD level when the charging station is connected to Kahramaa LV panels or directly supplied by 11kV feeder. It can be simply stated that for higher rated EVCS in range of MWs, it is recommended to powered from the MV feeder while the small rated ones to be distributed along the LV network. However, this assumption needs to be verified in order to determine the level of THD in both 11kV and 415V feeders respectively.

6.2 Modeling and Simulation Unbalanced QEWC Distribution Network

In this chapter, the distribution network, models of a unbalanced branch of Qatar distribution network at 11 kV and 415 V voltage level sides with 1600 kVA rated transformers as per QEWC standards, has been simulated using MATLAB/SIMULINK. This simulation aims to investigate the impact of 400 V, 16 kW EV charging station's penetration on the public grid in terms of THD percentage. As shown in Figure 6.1, the EVCSs have been connected at bus 634 and 675 with 126 kW, 110 kVAR, and 485 kW, 190 kVAR connected loads, respectively. The EVCS and EV rated voltage and power is 400 V and 16 kW, respectively, and the results are shown in Figure 6.2.

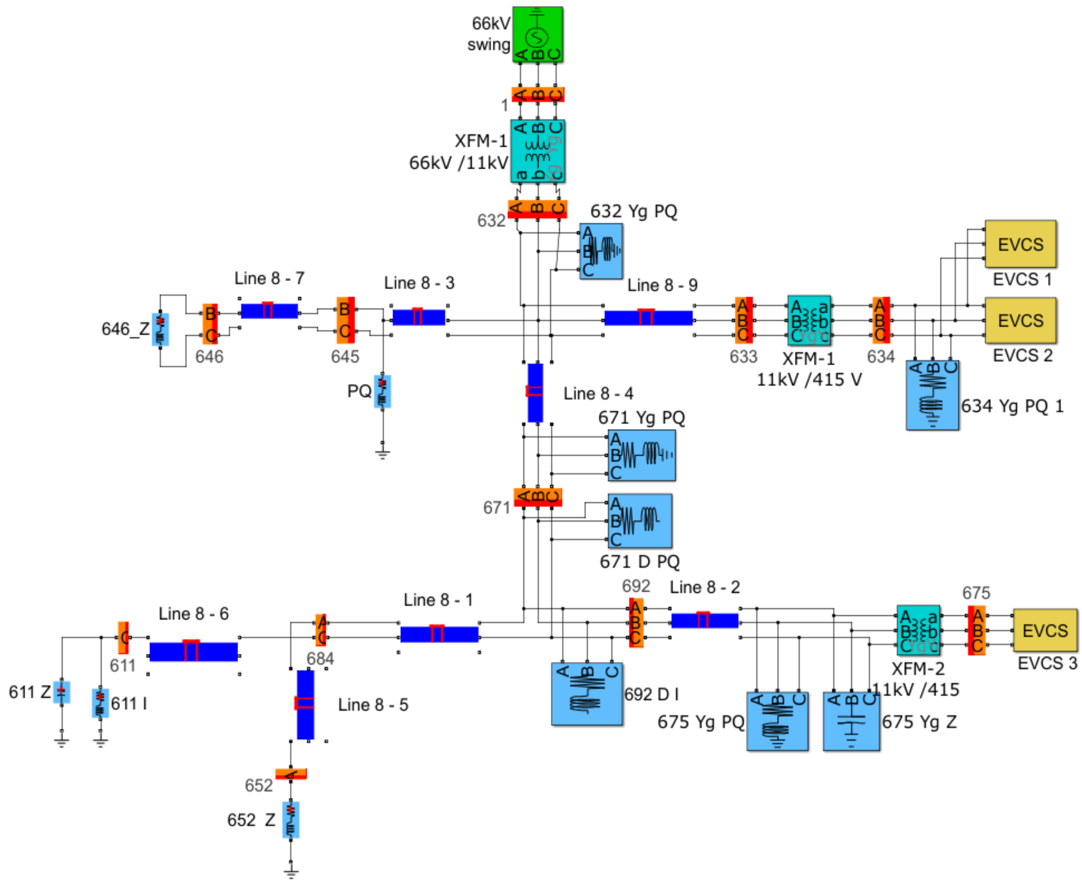

Figure 6.1. EVCS-connected unbalanced distributiion network.

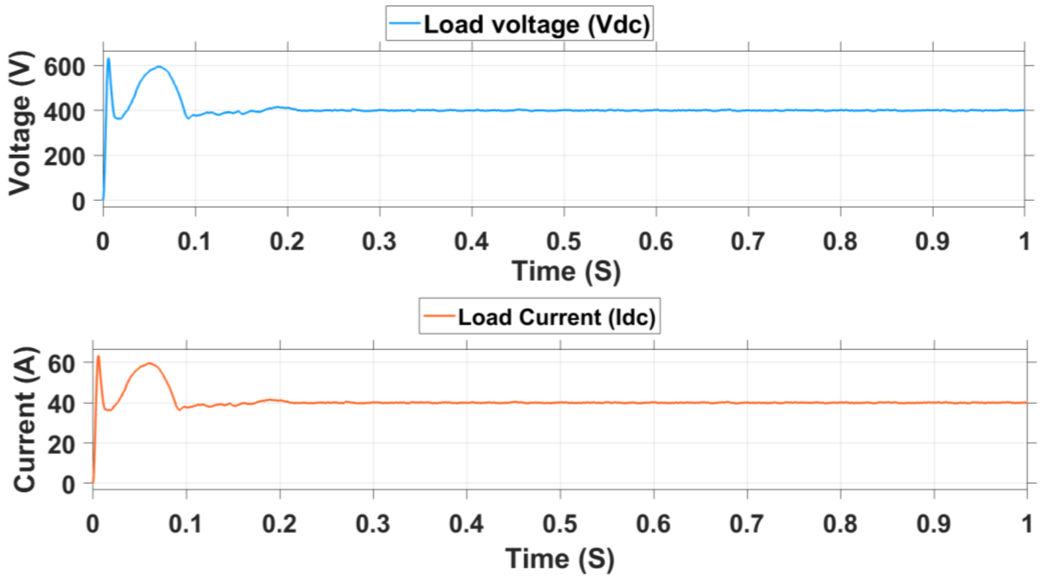

Figure 6.2. 16kW EVCS output voltage and current.

6.3 Evaluation of EVCS Penetration Impact on Various Distribution Buses

In the beginning, the THD level has been investigated at the 11 kV side with one EVCS connected to bus 634. The results show smooth waveform with 0.33% THD as shown in Figure 6.3 and 6.4 respectively. However, when the measurement is taken at the 415 V side, the results were 2.11%, as shown in Figure 6.6, and the voltage waveform experiences evident distortion as shown in Figure 6.5.

Moreover, when EVCS is connected to the 675 bus, the values of THD change slightly. On the medium voltage side, the value was 0.29%, while on the low voltage side, it increases by 0.08 percentage to reach 2.19%. The results have been shown in Figure 6.7 and 6.8 for the 11 kV side and Figure 6.9 and 6.10 for the 415 V side, respectively.

From the above discussion, it can be stated that medium voltage shows a robust response to the penetration of EVCS and gives a chance to a large isolated EV charging plant to be connected directly to the 11 kV side. Nevertheless, at the 415 V side, where the EVCS most probably will be connected with other loads that can be sensitive to a high THD value, the bus experiences high distortion levels that will limit its ability to accept more EVCS. Hence, it can be used for small isolated areas where the demand for EV charging is relatively small compared to the city's downtowns and center.

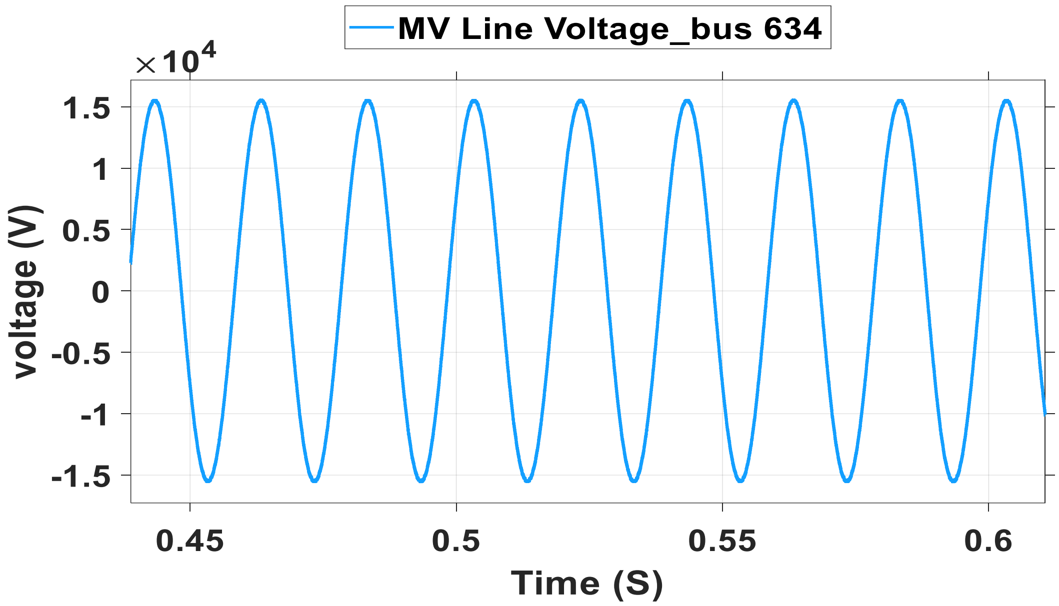

Figure 6.3. 11kV line voltage at bus 634.

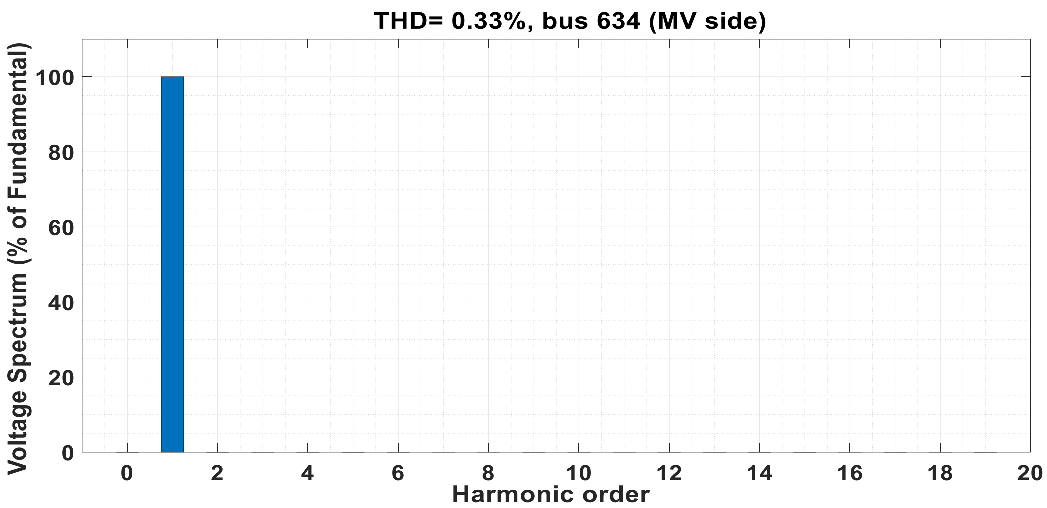

Figure 6.4. THD level at bus 634 (MV side).

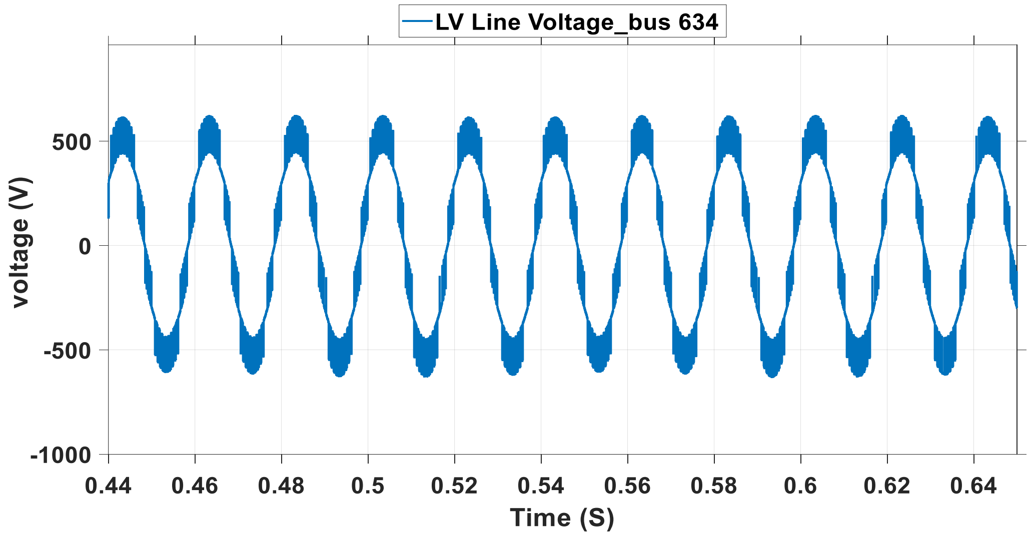

Figure 6.5. 415V line voltage at bus 634.

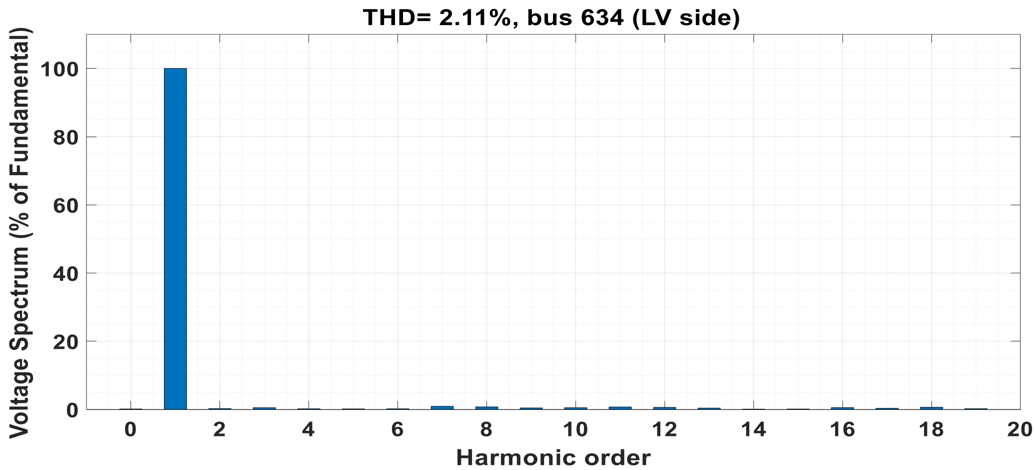

Figure 6.6. THD level at bus 634 (LV side).

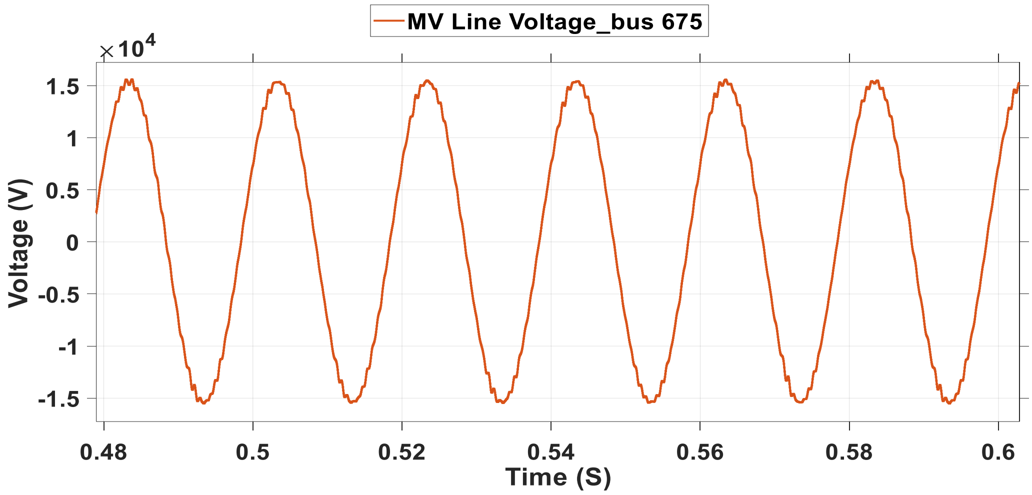

Figure 6.7. 11kV line voltage at bus 675.

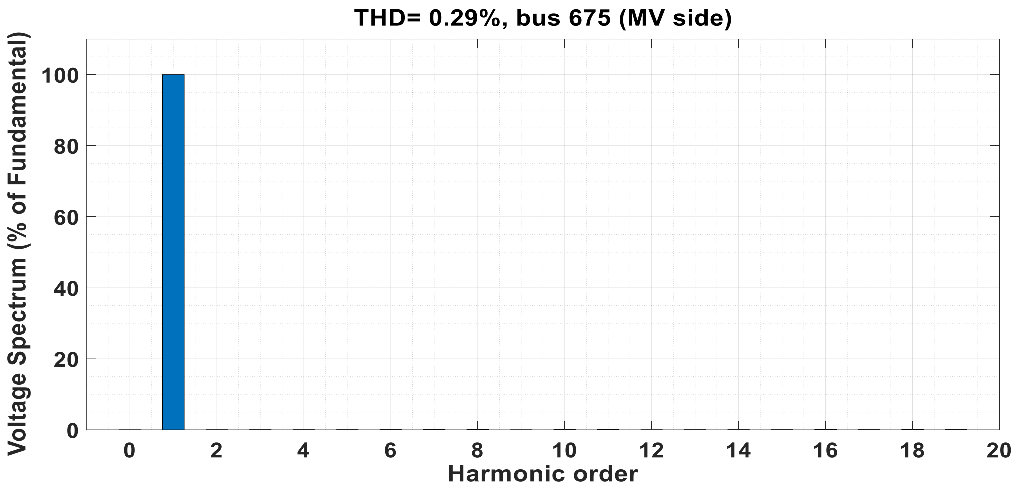

Figure 6.8. THD level at bus 675 (MV side).

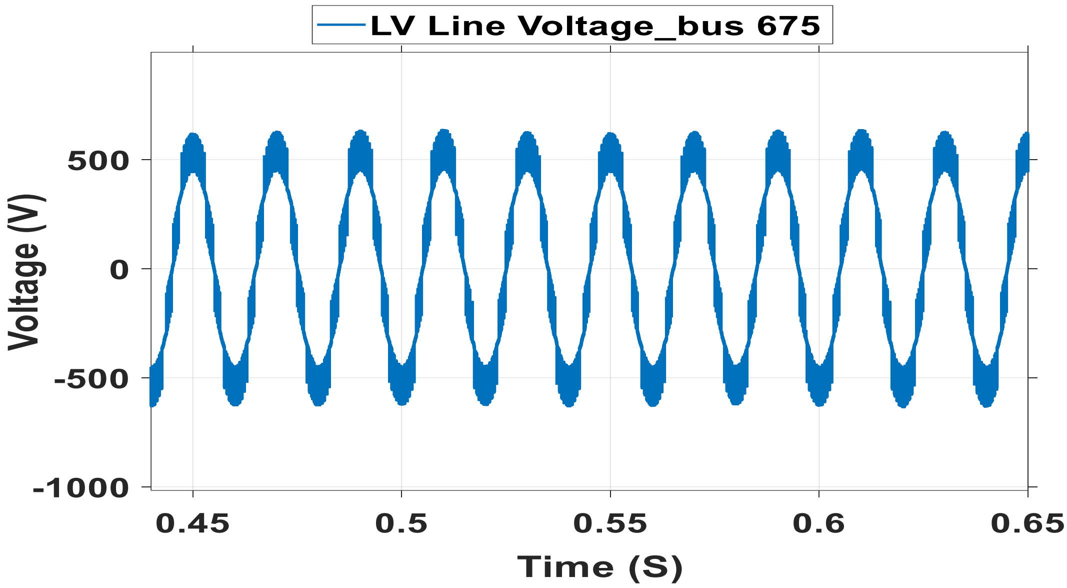

Figure 6.9. 415V line voltage at bus 675.

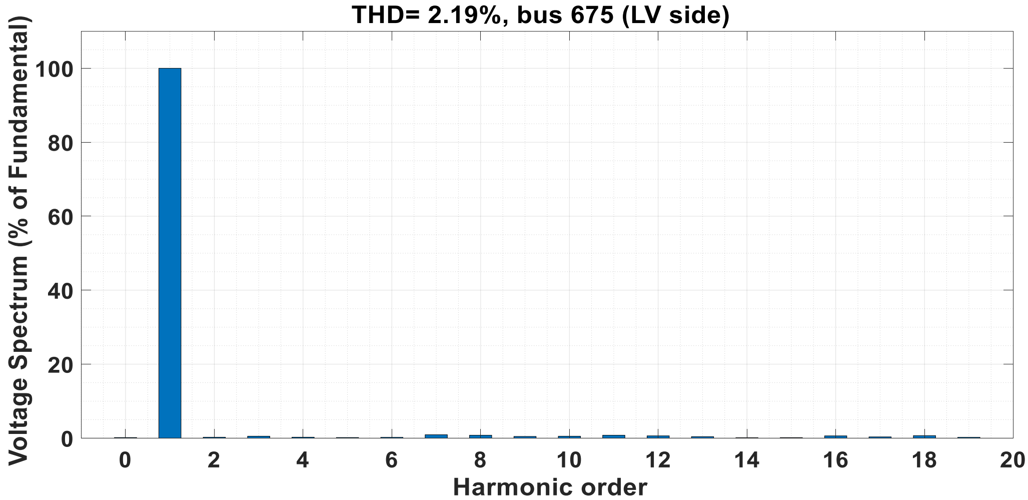

Figure 6.10. THD level at bus 675 (LV side).

6.4 Impact of EVCS Penetration Increase on 11kv and 415V Buses THD Level

The second scenario in this chapter is to connect more than one EVCS to the same bus while keeping the other bus attached to one EVCS. Figures 6.11 shows smooth voltage waveform and harmonic spectrum in Figure 6.12 results in THD value of 0.43% from the 11 kV side when two EVCSs are connected to bus 634.

It is considered a small value that opens the possibility of increasing the number of attached EVCS before the allowable standard value is reached. However, looking at the THD value from the low voltage side, THD increases from 2.11% to 3.45%, as shown in Figures 6.14 when the number of connected EVCS increases limiting the bus's capacity to accommodate more charging points. The voltage signal experiences a considerable contamination as it appeared in Figure 6.13.

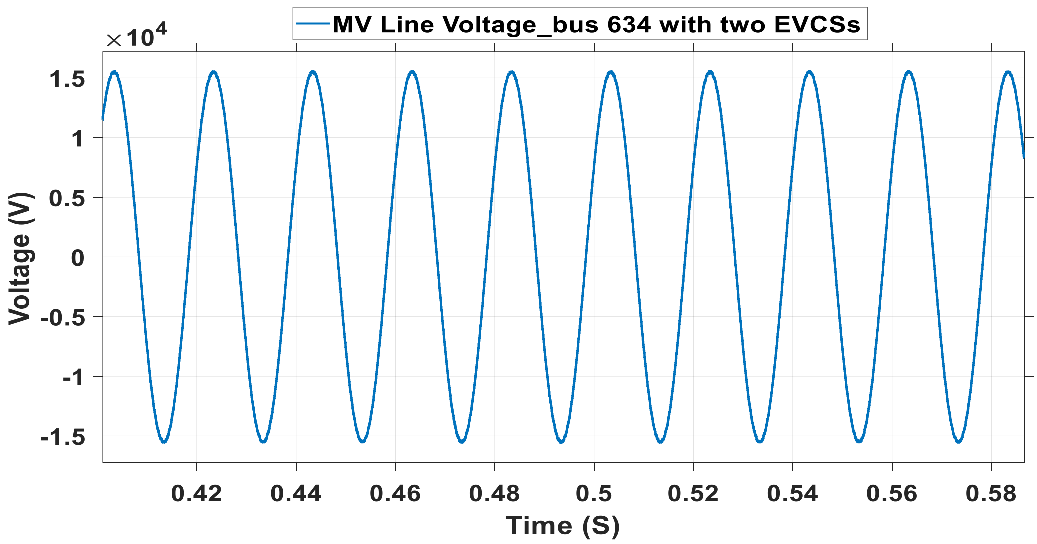

Figure 6.11. 11kV line voltage at bus 634 with penetration of two EVCSs.

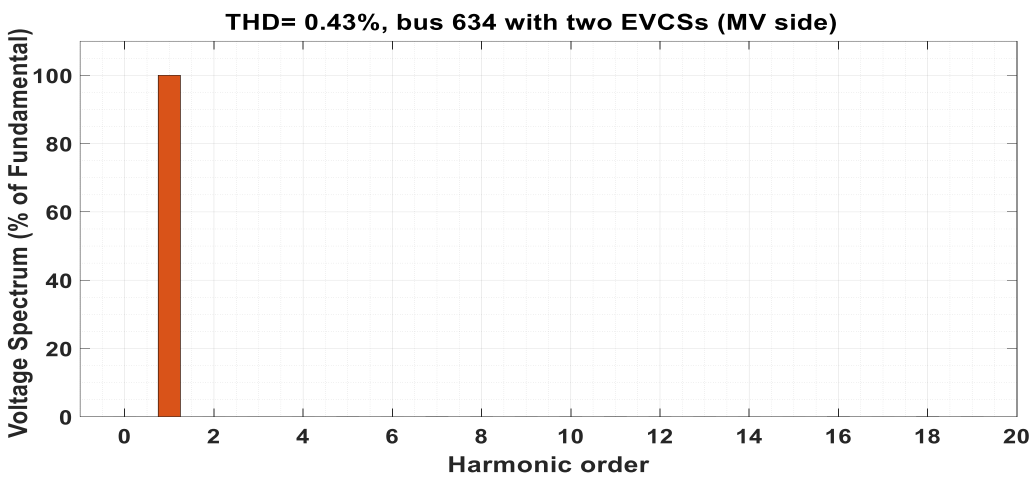

Figure 6.12. THD level at bus 634 with penetration of two EVCSs (MV side).

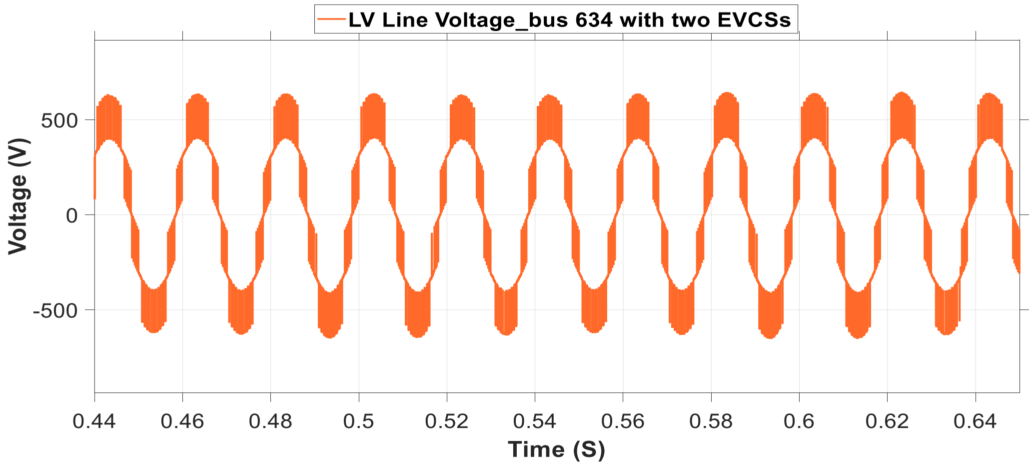

Figure 6.13. 415V line voltage at bus 634 with penetration of two EVCSs.

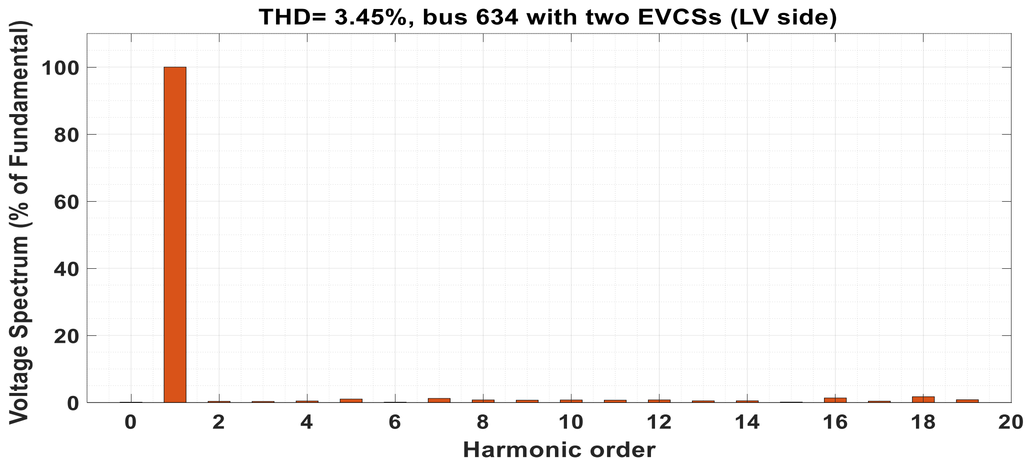

Figure 6.14. THD level at bus 634 with penetration of two EVCSs (LV side).

The total harmonic distortion has been investigated in this study from power utility point view where the focus centralized on voltage waveform. However, the EVCS manufacturers need to analyze the harmonic distortion content of the current in order to optimize the design of the charging stations and maintain current THD within standard limit. In the next section, the impact of EVCS on voltage profile is investigated in order to determine the amount of energy that can be utilized at the targeted bus before the voltage limit is violated.

6.5 Summary

Harmonic distortion in the voltage waveform at the load side is one of the main problems encountered when large numbers of EV charging stations are connected to the public distribution network. It is essential to distinguish between large EV centralized charging plants connected directly to the medium voltage and distributed charging stations scattered in the city and connected to the low voltage side. This distinction has been made because the level of harmonic distortion is highly different on both sides. The design of power converters and EV batteries can be of high importance in the mitigation of THD to meet the specified standard and increase EVCS attached to the grid. In this chapter, simulation is performed for 16 kW, 400 V EVCS. However, to assess the impact of fast charging on the THD content, 50 kW or above rated EVCS is considered. From the above discussed results, it can be concluded that a large EVCS should be connected to a dedicated 11 kV feeder. It can be realized for up to a 5 MW EVCS plant as per QEWC standards. On the other hand, small EVCS in the range of kW can be integrated into the low voltage grid in a distributed manner.

Chapter 7: Conclusion and Future Work

7.1 Observations and recommendations

The electrification of the transport sector plays crucial role in present and future visions of many countries around the world and several vehicle manufacturers put plans already in order to transform from conventional gas-fueled cars to EVs or PHEVs in the short and medium future ranges. One of the main changes that are going to accompany EV revolution is infrastructure development in terms of optimal placement of public fast charging EV charging stations, underground services for auxiliary systems, public grid integration and many other related logistic factors to ensure service quality and reliability. Although, there are alternative renewable energy sources that can supply EV required demand, it is the public grid that has the ability to power large fleet of E-bus public transportation that is going to serve crowded and congested modern cities. Moreover, if EV revolutionary vision to succeed, it requires public EV charging stations that are located optimally around the city to be interconnected to reliable power supplier such as local public grid. For that, Qatar has included in its 2030 vision and beyond to transform part of its public sector to be electrical-powered type such as school buses, public train as well as in the labor cities. As part of that vision, Kahramaa as the main power provider and ministry of transportation and communication (MOTC) have start a joint project to construct fast charging public EVCSs and to be located optimally in order to serve the majority of the sectors and the public at large.

However, integrating EVCS into Kahramaa grid comes at a price and hence intensive studies need to be conducted in order to determine the negative impacts that these EVCSs will impose on the public grid before starting the tendering process and issuing the official approvals.

Part of these impacts have been investigated thoroughly in this thesis for several EVCS brands and it is concluded in the discussion that different charging stations show various impact on the grid main parameters such as harmonic distortion at the common coupling point (CCP), voltage drop and power losses. for example, in terms of THD level, type 3 shows the best results with less than 0.5% while type 1 scores the highest level and THD percentages were more than 3% giving less margins to increase EVCS penetration. Moreover, all the EVCS types operate within Kahramaa voltage drop standard of 6% except for type 2 at certain distribution feeders where the bus voltage peak value reaches 540.4V with almost 10V drop below the minimum limit of 551.6V. For the power losses, the distribution network performs similarly with the integration of type 1 and 2 where the percentage total losses of 2.44%. however, the minimum system losses are achieved when type 3 is integrated with 0.35% of the total losses.

One of the solution that has been proposed in this study to mitigate these impacts is the integration of RES near the EVCS panel to supply part of its load. However, integration of RES may raise new challenges to the grid. For instance, PV source can generate reactive power that is not intended to inject into the system and hence, the voltage may rise to severe levels and damage the equipment. Moreover, integration of EVCS and without smart strategic charging process, the maximum demand will surge during peak time and this may cause several problems such as supply shortage in some areas, false tripping due to rise in demand current in other areas as well as increase in power losses. for that, it is highly important to construct coordinated load sharing control strategies to overcome these challenges and that alone is part of another extensive research in the literature of the field.

In general, the major conclusions can be stated in the following points:

- Integration of EVCS type 3 is the optimal selection when the distribution network suffers from large non-linear loads
- For the feeders that supply heavy loads or remote areas where the voltage drop is the main constraint, a combination of type 1 and 3 is considered the optimal solution
- The integration of renewable energy source (RES) at EVCS-connected feeders improves the system performance
- Increasing the penetration of RES into the distribution network may increase THD level and have reverse negative impact.

7.2 Future Work

In future work, the focus of this study will be shifted to investigate the optimal location and operation of EV charging stations in terms of charging prices, queue waiting time as well as the availability of the spare capacity at the targeted charging station. From Kahramaa point view, the EV charging station should be located optimally in places where there is spare capacity in the nearby distribution feeders and hence they can supply EV required load in that area. However, from MOTC perspective, the waiting time, the travelled distance between the EV and the closest EVCS are the major concerns regarding the optimal location for EVCS. Moreover, in addition to all these optimization problems, EV private owners concern more about the price of charging and hence would like to charge from the nearest cheaper EVCS.

All these challenges will pave the new paths of this research in order to investigate them and to be formulated mathematically using the proper optimization techniques taking into consideration the nature of Kahramaa infrastructure rules and regulations.

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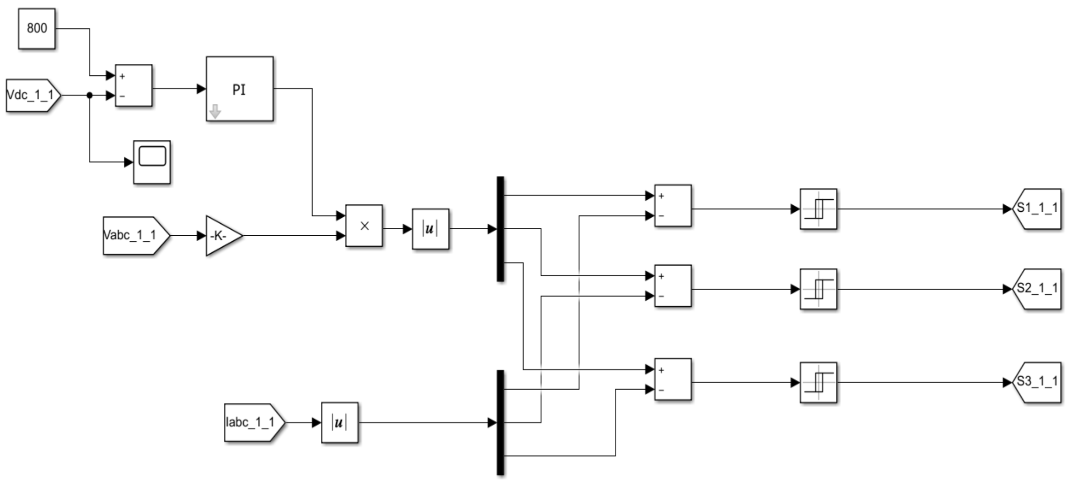
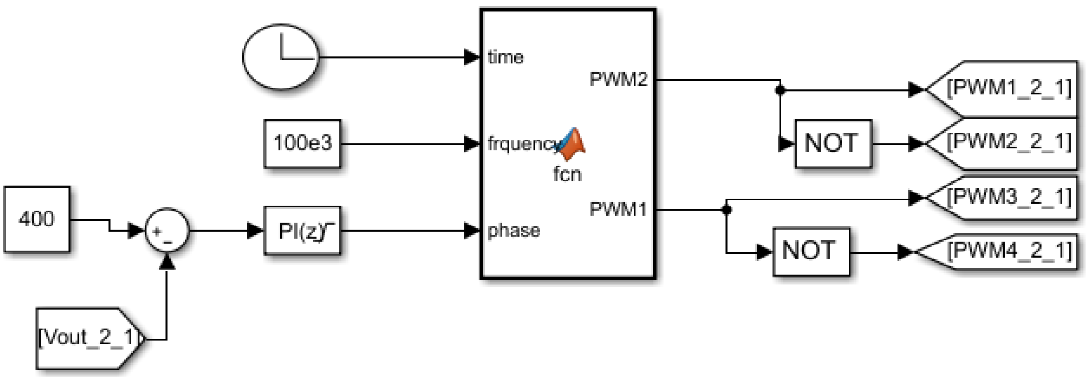
APPENDICES

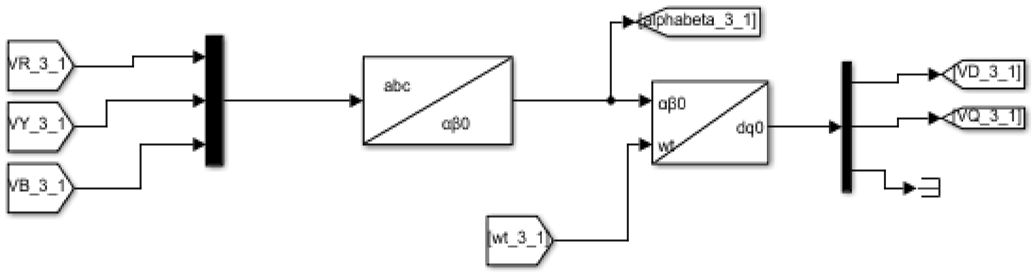
Appendix A: List of Publications

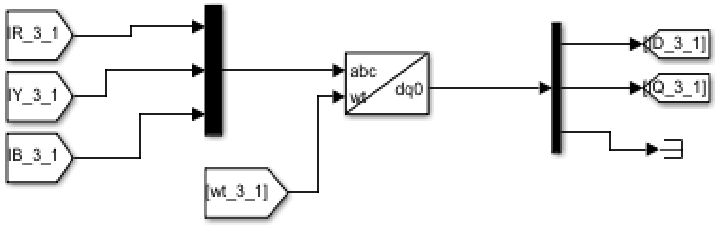
Paper Title	Conference/Journal Name
Impact of EV charging Station Penetration on Harmonic Distortion Level in Utility Distribution Network: A Case Study of Qatar	IEEE Texas Power and Energy Conference (TPEC 2021), held virtually on February 2-5, 2021

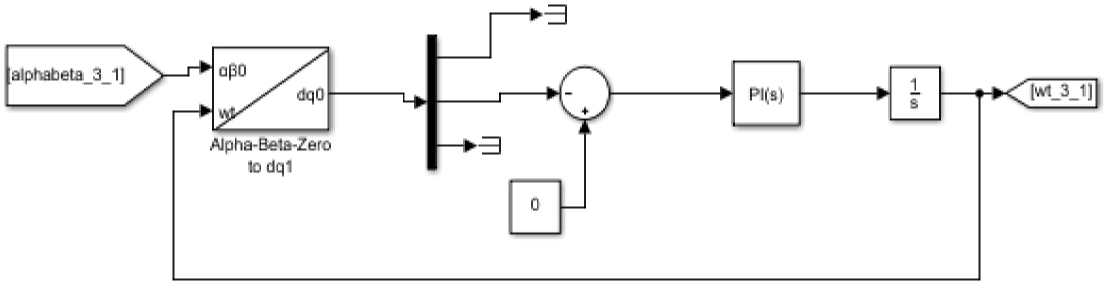
Appendix B: Control Block Diagrams

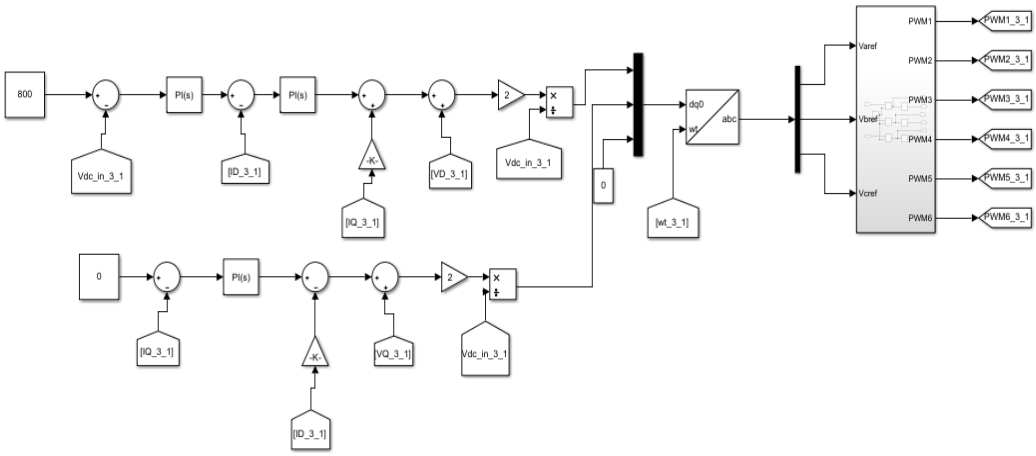




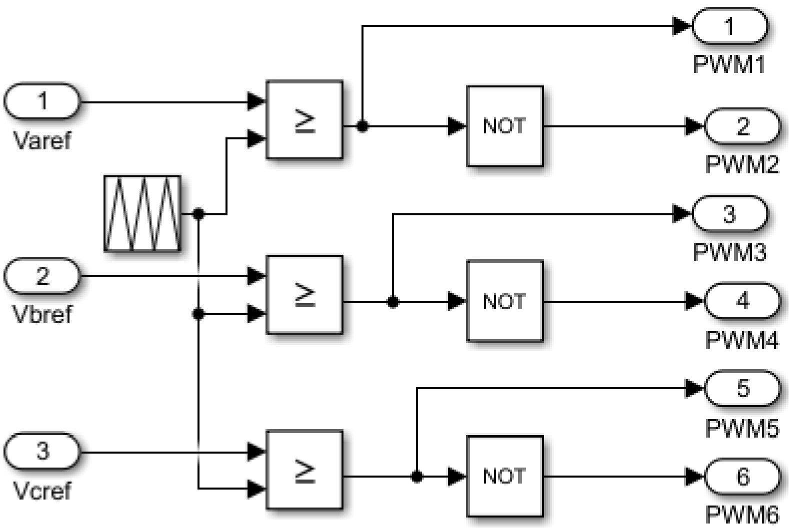

VR_3_1
VY_3_1
VB_3_1
abc
αβ0
[alphabeta_3_1]
αβ0
wt
dq0
[VD_3_1]
[VQ_3_1]
[wt_3_1


IR_3_1
IY_3_1
IB_3_1
abc
wt
dq0
[wt_3_1]
[ID_3_1]
[IQ_3_1]


[alphabeta_3_1]
αβ0
wt
dq0
Alpha-Beta-Zero
to dq1
-
+
0
PI(s)
1
s
[wt_3_1]



800
PI(s)
PI(s)
2
Vdc_in_3_1
[ID_3_1]
-K-
[IQ_3_1]
[VD_3_1]
Vdc_in_3_1
0
dq0
wt
abc
[wt_3_1]
Varef
Vbref
Vcref
PWM1
PWM2
PWM3
PWM4
PWM5
PWM6
PWM1_3_1
PWM2_3_1
PWM3_3_1
PWM4_3_1
PWM5_3_1
PWM6_3_1
0
PI(s)
2
[IQ_3_1]
-K-
[ID_3_1]
[VQ_3_1]
Vdc_in_3_1



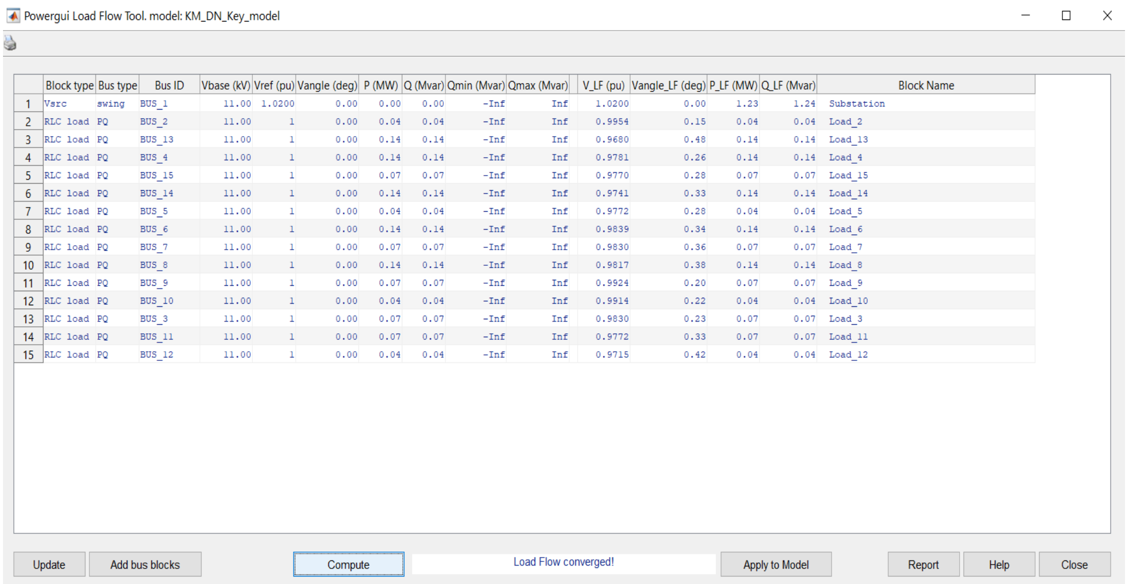
1
Varef
2
Vbref
3
Vcref
≥
≥
≥
NOT
NOT
NOT
1
PWM1
2
PWM2
3
PWM3
4
PWM4
5
PWM5
6
PWM6

```
function [PWM2, PWM1]= fcn(time,frquency,phase)
Tswitching=1/frquency;
PWM1=0;
PWM2=0;
y1=mod(time,Tswitching);
if y1<Tswitching/2
PWM1=1;
end
t_phi=Tswitching*phase/360;
y2=mod(time+t_phi,Tswitching);
if y2<Tswitching/2
    PWM2=1;
end
```

```
function Vref = RefGen(V,I)

Vrefmax=363;
Vrefmin=0.0;
Vrefinit=300;
deltaVref=1;
persistent Vold Pold Vrefold;

dataType='double';

if isempty(Vold)
    Vold=0;
    Pold=0;
    Vrefold=Vrefinit;
end
P=V*I;
dV=V-Vold;
dP=P-Pold;

if dP~=0
    if dP<0
        if dV<0
            Vref=Vrefold+deltaVref;
```

```
            else
                Vref=Vrefold-deltaVref;
            end
        else
            if dV<0
                Vref=Vrefold-deltaVref;
            else
                Vref=Vrefold+deltaVref;
            end
        end
    else Vref=Vrefold;
    end
    if Vref>=Vrefmax | Vref<=Vrefmin
        Vref=Vrefold;
    end
    Vrefold=Vref;
    Vold=V;
    Pold=P;
```

Appendix D: Power Flow



	Block type	Bus type	Bus ID	Vbase (kV)	Vref (pu)	Vangle (deg)	P (MW)	Q (Mvar)	Qmin (Mvar)	Qmax (Mvar)	V_LF (pu)	Vangle_LF (deg)	P_LF (MW)	Q_LF (Mvar)	Block Name
1	Vsrc	swing	BUS_1	11.00	1.0200	0.00	0.00	0.00	-Inf	Inf	1.0200	0.00	1.23	1.24	Substation
2	RLC load	PQ	BUS_2	11.00	1	0.00	0.04	0.04	-Inf	Inf	0.9954	0.15	0.04	0.04	Load_2
3	RLC load	PQ	BUS_13	11.00	1	0.00	0.14	0.14	-Inf	Inf	0.9680	0.48	0.14	0.14	Load_13
4	RLC load	PQ	BUS_4	11.00	1	0.00	0.14	0.14	-Inf	Inf	0.9781	0.26	0.14	0.14	Load_4
5	RLC load	PQ	BUS_15	11.00	1	0.00	0.07	0.07	-Inf	Inf	0.9770	0.28	0.07	0.07	Load_15
6	RLC load	PQ	BUS_14	11.00	1	0.00	0.14	0.14	-Inf	Inf	0.9741	0.33	0.14	0.14	Load_14
7	RLC load	PQ	BUS_5	11.00	1	0.00	0.04	0.04	-Inf	Inf	0.9772	0.28	0.04	0.04	Load_5
8	RLC load	PQ	BUS_6	11.00	1	0.00	0.14	0.14	-Inf	Inf	0.9839	0.34	0.14	0.14	Load_6
9	RLC load	PQ	BUS_7	11.00	1	0.00	0.07	0.07	-Inf	Inf	0.9830	0.36	0.07	0.07	Load_7
10	RLC load	PQ	BUS_8	11.00	1	0.00	0.14	0.14	-Inf	Inf	0.9817	0.38	0.14	0.14	Load_8
11	RLC load	PQ	BUS_9	11.00	1	0.00	0.07	0.07	-Inf	Inf	0.9924	0.20	0.07	0.07	Load_9
12	RLC load	PQ	BUS_10	11.00	1	0.00	0.04	0.04	-Inf	Inf	0.9914	0.22	0.04	0.04	Load_10
13	RLC load	PQ	BUS_3	11.00	1	0.00	0.07	0.07	-Inf	Inf	0.9830	0.23	0.07	0.07	Load_3
14	RLC load	PQ	BUS_11	11.00	1	0.00	0.07	0.07	-Inf	Inf	0.9772	0.33	0.07	0.07	Load_11
15	RLC load	PQ	BUS_12	11.00	1	0.00	0.04	0.04	-Inf	Inf	0.9715	0.42	0.04	0.04	Load_12

```
SUMMARY for subnetwork No 1

  Total generation  : P=      1.23 MW Q=      1.24 Mvar
  Total PQ load     : P=      1.18 MW Q=      1.20 Mvar
  Total Zshunt load : P=      0.00 MW Q=     -0.00 Mvar
  Total ASM load    : P=      0.00 MW Q=      0.00 Mvar
  Total losses      : P=      0.06 MW Q=      0.04 Mvar
```

```
1 : BUS_1  V= 1.020 pu/11kV 0.00 deg  ; Swing bus
        Generation : P=    1.23 MW Q=    1.24 Mvar
        PQ_load    : P=    0.00 MW Q=    0.00 Mvar
        Z_shunt    : P=    0.00 MW Q=   -0.00 Mvar
   -->  BUS_2      : P=    1.23 MW Q=    1.24 Mvar

2 : BUS_10  V= 0.991 pu/11kV 0.22 deg
        Generation : P=    0.00 MW Q=    0.00 Mvar
        PQ_load    : P=    0.04 MW Q=    0.04 Mvar
        Z_shunt    : P=    0.00 MW Q=   -0.00 Mvar
   -->  BUS_9      : P=   -0.04 MW Q=   -0.04 Mvar

3 : BUS_11  V= 0.977 pu/11kV 0.33 deg
        Generation : P=    0.00 MW Q=    0.00 Mvar
        PQ_load    : P=    0.07 MW Q=    0.07 Mvar
        Z_shunt    : P=    0.00 MW Q=   -0.00 Mvar
   -->  BUS_12     : P=    0.17 MW Q=    0.18 Mvar
   -->  BUS_3      : P=   -0.24 MW Q=   -0.25 Mvar

4 : BUS_12  V= 0.972 pu/11kV 0.42 deg
        Generation : P=    0.00 MW Q=    0.00 Mvar
        PQ_load    : P=    0.04 MW Q=    0.04 Mvar
        Z_shunt    : P=    0.00 MW Q=   -0.00 Mvar
   -->  BUS_11     : P=   -0.17 MW Q=   -0.18 Mvar
   -->  BUS_13     : P=    0.13 MW Q=    0.13 Mvar

5 : BUS_13  V= 0.968 pu/11kV 0.48 deg
        Generation : P=    0.00 MW Q=    0.00 Mvar
        PQ_load    : P=    0.13 MW Q=    0.13 Mvar
        Z_shunt    : P=    0.00 MW Q=   -0.00 Mvar
   -->  BUS_12     : P=   -0.13 MW Q=   -0.13 Mvar

6 : BUS_14  V= 0.974 pu/11kV 0.33 deg
        Generation : P=    0.00 MW Q=    0.00 Mvar
        PQ_load    : P=    0.13 MW Q=    0.14 Mvar
        Z_shunt    : P=    0.00 MW Q=   -0.00 Mvar
   -->  BUS_4      : P=   -0.13 MW Q=   -0.14 Mvar

7 : BUS_15  V= 0.977 pu/11kV 0.28 deg
        Generation : P=    0.00 MW Q=    0.00 Mvar
        PQ_load    : P=    0.07 MW Q=    0.07 Mvar
        Z_shunt    : P=    0.00 MW Q=   -0.00 Mvar
   -->  BUS_4      : P=   -0.07 MW Q=   -0.07 Mvar

8 : BUS_2  V= 0.995 pu/11kV 0.15 deg
        Generation : P=    0.00 MW Q=    0.00 Mvar
```

```
        PQ_load     : P=    0.04 MW Q=    0.05 Mvar
        Z_shunt     : P=   -0.00 MW Q=   -0.00 Mvar
   -->  BUS_1       : P=   -1.20 MW Q=   -1.22 Mvar
   -->  BUS_3       : P=    0.70 MW Q=    0.71 Mvar
   -->  BUS_6       : P=    0.34 MW Q=    0.35 Mvar
   -->  BUS_9       : P=    0.11 MW Q=    0.11 Mvar

9 : BUS_3  V= 0.983 pu/11kV 0.23 deg
        Generation : P=    0.00 MW Q=    0.00 Mvar
        PQ_load     : P=    0.07 MW Q=    0.07 Mvar
        Z_shunt     : P=   -0.00 MW Q=   -0.00 Mvar
   -->  BUS_11      : P=    0.24 MW Q=    0.25 Mvar
   -->  BUS_2       : P=   -0.69 MW Q=   -0.70 Mvar
   -->  BUS_4       : P=    0.38 MW Q=    0.39 Mvar

10 : BUS_4  V= 0.978 pu/11kV 0.26 deg
        Generation : P=    0.00 MW Q=    0.00 Mvar
        PQ_load     : P=    0.13 MW Q=    0.14 Mvar
        Z_shunt     : P=    0.00 MW Q=   -0.00 Mvar
   -->  BUS_14      : P=    0.13 MW Q=    0.14 Mvar
   -->  BUS_15      : P=    0.07 MW Q=    0.07 Mvar
   -->  BUS_3       : P=   -0.38 MW Q=   -0.38 Mvar
   -->  BUS_5       : P=    0.04 MW Q=    0.04 Mvar

11 : BUS_5  V= 0.977 pu/11kV 0.28 deg
        Generation : P=    0.00 MW Q=    0.00 Mvar
        PQ_load     : P=    0.04 MW Q=    0.04 Mvar
        Z_shunt     : P=    0.00 MW Q=   -0.00 Mvar
   -->  BUS_4       : P=   -0.04 MW Q=   -0.04 Mvar

12 : BUS_6  V= 0.984 pu/11kV 0.34 deg
        Generation : P=    0.00 MW Q=    0.00 Mvar
        PQ_load     : P=    0.14 MW Q=    0.14 Mvar
        Z_shunt     : P=    0.00 MW Q=   -0.00 Mvar
   -->  BUS_2       : P=   -0.34 MW Q=   -0.35 Mvar
   -->  BUS_7       : P=    0.07 MW Q=    0.07 Mvar
   -->  BUS_8       : P=    0.14 MW Q=    0.14 Mvar

13 : BUS_7  V= 0.983 pu/11kV 0.36 deg
        Generation : P=    0.00 MW Q=    0.00 Mvar
        PQ_load     : P=    0.07 MW Q=    0.07 Mvar
        Z_shunt     : P=    0.00 MW Q=   -0.00 Mvar
   -->  BUS_6       : P=   -0.07 MW Q=   -0.07 Mvar

14 : BUS_8  V= 0.982 pu/11kV 0.38 deg
        Generation : P=    0.00 MW Q=    0.00 Mvar
        PQ_load     : P=    0.13 MW Q=    0.14 Mvar
```

```
        Z_shunt     : P=    0.00 MW Q=   -0.00 Mvar
   -->  BUS_6       : P=   -0.13 MW Q=   -0.14 Mvar

15 : BUS_9  V= 0.992 pu/11kV 0.20 deg
        Generation  : P=    0.00 MW Q=    0.00 Mvar
        PQ_load     : P=    0.07 MW Q=    0.07 Mvar
        Z_shunt     : P=    0.00 MW Q=   -0.00 Mvar
   -->  BUS_10      : P=    0.04 MW Q=    0.04 Mvar
   -->  BUS_2       : P=   -0.11 MW Q=   -0.11 Mvar
```