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Impact of Electric Vehicles Charging Stations on Egyptian Electricity Grid Including Two Operating Modes Grid to Vehicle and Vehicle to Grid

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Abstract— Electric Vehicles (EVs) increase rapidly nowadays because of their benefits such as preserving the environment and the public health. It is expected that EVs will replace all the traditional vehicles that depend on fossil fuels. Depending on renewable energy in charging the EVs, they are considered one of the cleanest means of transportation, so they are called green transportation. EVs will achieve great development in the transportation section all over the world and specially in Egypt. Egypt seeks to encourage usage of EVs. Egypt is planning to establish its infrastructure for EVs charging in the coming years. Studying the impacts of EVs Direct Current (DC) fast charging on the Egyptian electricity network is an important and essential need. This paper studies the impact of EVs Charging Stations (CSs) on the Egyptian electricity network through a practical simulation of CS during charging mode. This paper includes simulation results of a DC fast CS which includes three fast DC chargers with a total power of 120 kW. The charging station and its components, such as the transformer and cables, are modeled using MATLAB/Simulink. Not only the paper studies impact of charging mode but also the paper studies the impacts of discharging mode of EVs batteries on the same electricity grid which is called Vehicle to Grid Mode (V2G). Also, the paper suggests a solution to mitigate some of the negative effects of CSs on the electricity networks. The proposed solution will reduce the value of Total Harmonics Distortion (THD) in addition to the short circuit level. Also, the waveforms of currents and voltage will be enhanced.

Keywords: Electric Vehicles (EVs); EVs charging infrastructure; Charging Stations (CSs); CSs effects; Vehicle to Grid (V2G); Fast charging and EVs charging impacts; Total Harmonics Distortion (THD) reduction.

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1 Introduction

Electric Vehicles (EVs) have a lot of environmental benefits such as reducing greenhouse gases and carbon emissions [1]. It is considered an active solution for the phenomenon of global warming, air pollution, in addition to rationalizing the consumption of fossil fuels [2]. EVs have been spread worldwide, according to studies there are about three million EVs are currently in use all over the world [3]. EVs will rapidly increase, and their number may reach about 100 million by the year 2030 due to their advantages and benefits [3]. It is expected that EVs in Egypt will replace traditional vehicles in the near future [4]. Egypt's 2030 vision emphasizes enhancement of environmental aspects by depending on renewable energy sources and green transportation [5]. EVs are charged by electricity in Charging Station (CS) in public locations which is connected to electricity network [6]. Currently, many CSs are spread in Egypt that are totally connected to the electricity grid, and the recharging operation depends on electricity from the utility grid [7]. Because EVs chargers are considered non-linear load, they affect the electricity network by causing harmonics, current and voltage imbalances, reduction of power factor and other negative impacts [8].

Authors in [8] studied power quality issues and focused on harmonics represented by EVs CS at the node where they are connected to the electricity network and at reduced voltage levels by using IEEE 6-bus in addition to 14-bus, and 30-bus test power systems. Important power quality issues like harmonic, voltage imbalance, transformer power losses were studied considering Bangladesh electricity grid using MATLAB/Simulink in [9]. In [10], authors studied the effect of EVs CSs on a residential distribution system considering smart inverters and an actual case study was considered to get nodes voltages and feeders currents. In [11], Authors studied the effects of adding EVs loads on the total load losses, temperature and the aging factor by considering a 100 kVA Distribution Transformer (DT). Authors in [12] evaluated impacts of changing different parameters of the distribution system on both primary and secondary circuit voltage levels occurred under EVs charging loads.

Many paper study impacts of EVs charging through test systems such as IEEE (6,14,30) buses [8]. There are a few papers that study the impacts of the EVs charging on the electricity grid by modeling a charging station and its components. No prior work has examined the effect of Direct Current (DC) fast charging station on Egyptian electricity grid.

This paper studies the power quality issues on electricity grid due to DC fast charging station. A charging station with a total power of 120 kW connected to a 500 kVA distribution transformer is considered in it. Four different scenarios are assumed to obtain the results in the paper. These four scenarios describe the possible operation cases of the charging station. Also, this paper suggests a solution for the power quality issues due to DC fast charging station.

The paper includes seven sections. The rest of the paper is organized in the following way. Section 2 includes the impacts of DC fast charging on electricity grid. In section 3, the case study is explained and discussed. The simulation results are mentioned in section 4. Section 5 suggests a solution to mitigate DC CS's negative impacts. Section 6 discusses the impact of Vehicle to Grid (V2G) mode on the electricity grid. Finally, section 7 contains a conclusion of the paper and discusses the possible future work.

2 Impacts of Electric Vehicles DC Fast Charging and Vehicle to Grid Technology

2.1 Positive impacts of EVs DC fast charging

EVs have many positive impacts on the electricity grid such as frequency and voltage regulation, supporting more renewable energy resources in addition to reduction of peak loads by acting as power source for electricity grid [13]. EVs play an important role in grid stability as well as decreasing development of utility grid [6]. EVs CSs may be used in electricity as a power management tool which gives more flexibility [2].

2.2 Negative impacts of EVs DC fast charging

EVs charging will increase power demand on electricity grid [14]. Charging EVs causes harmonics and affects the power quality of the electricity grid [15]. EVs charging causes overloading of electricity network in addition to increasing both energy and power losses [16]. EVs charging loads consume huge electrical power in short instants, which may cause unstable operation in the electricity grid [17]. EVs charging causses transients, voltage dips, short-term overvoltage, current and voltage unbalancing, voltage interruptions, flickering, and single phasing which affects stable operation of the grid and new aspects must be considered to reduce these power quality issues [18]. EVs cause a voltage drop in the distribution network as a study shows that CS causes voltage to be less than 96 % of its nominal value due to this CS [19]. EVs charging loads may cause phases imbalance due to unbalanced charging load [20]. Wide spreading of EVs CSs can cause more stress on DTs, leading to a shortened their lifetime [6].

2.3 Vehicle to grid technology and its effects

V2G is an example of Vehicle-to-Everything (V2X) technology. The X letter may be grid, building, home or load. The technology of V2X transforms EVs into a moveable power source which can provide electrical power for the electricity grid directly or to a single building or a home for example. V2G needs bidirectional chargers or converters because the electricity may flow from grid to vehicle and this is the charging mode or from the vehicle to the grid and this is the discharging mode [6].

It benefits both the EV owners and the grid operators by reducing the high cost of electricity generation in peak hours, in addition to providing some profit for EVs owners. Not only economic value but also achieving an improvement in the electricity grid characteristics and performance in peak load hours.

V2G can be used for improved power grid transient stability and robustness [21]. It helps in achieving voltage and frequency regulation. V2G provides a solution to mitigate intermittency of renewable energy sources by providing electricity in case of any reduction of energy production from renewable energy sources. Also, V2G provides a standby power source which may be used in emergency cases. Moreover, it helps the electricity grid to have more flexibility as it has a power source which can be used to flatten the peak demands or reduce the overall cost in addition to reducing the need to build new generation stations [2].

3 Charging Station Specification and the Case Study

This paper studies the effect of DC fast charging through a charging station which includes three DC fast chargers. **Figure 1** shows a schematic diagram of the system which is studied in the paper.

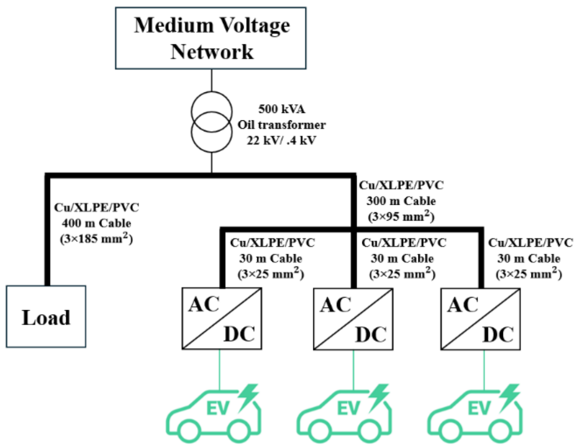

Fig. 1 A schematic diagram of the charging station

Each charger in the CS has a power rating of 40 kW and connected to the Distribution Panel (DP) through (3×25 mm^2) copper cable. The DP is connected to DT with (3×95 mm^2) copper cable. DT which is used in the system has typical parameters of a DT widespread in the Egyptian electricity grid. A load of 250 kVA is connected to the same DT via (3×185 mm^2) copper cable. Medium voltage network was modeled by a 22 kV feeder that has a total length of 19 km. This feeder was supplied by power from a high voltage network through a power transformer. **Table 1** shows the main parameters of the CS.

Table 1 Main parameters of the charging station

Main components of the CS				
Component	**Power**	**Voltage**	**X/R**	**Impedance**
Charger	40 kW	400 V	-	
Transformer	500 kVA	22 /.4 kV	.667	4%
Load	250 kVA	400 V	-	-
Cables				
Cable Number	**Location**	**Cross Section Area**	**Resistance**	**Inductance**
Cable 1	From transformer to the DP of the CS	(3×95) mm^2	75 mΩ	69.6 µH
Cable 2	From the DP to the charger	(3×25) mm^2	28 mΩ	7.954 µH
Cable 3	From transformer to the load	(3×185) mm^2	52 mΩ	92.27 µH
Feeders				
The feeder	**Voltage**	**Length**	**Load-1 on Feeder**	**Load-2 on Feeder**
Medium Voltage Feeder	22 kV	19 km	2 MW	30 MW + 2 Mvar

The model of the used charger is adapted from the model in [22]. There are two operating modes. First operation mode is the normal operating mode in which the CS considered as a load on grid. Mode one is called grid to vehicle (G2V) in which power flows from grid to recharge vehicles [23]. The first mode includes three different scenarios. In the first scenario, there is only one charger which operates with full charging power. In the second scenario, there are two chargers operating with full charging power. In the third scenario, the three chargers operate with full charging power. Second operation mode is used while there is a peak load on the DT. In the second operation mode, the CS is considered as a power source for the electricity grid. The second mode is called V2G in which power flows from the CS to help in supplying the loads in peak hours [24].

Second mode includes the fourth scenario in which the CS acts as a power supply. Supposing a peak hour in the fourth scenario, loads which are connected to DT increase to around 620 kVA which is more than DT rating by 120 kVA. The charging station can inject this excessive power into the grid to supply load in this peak hour. That is done by the operation of the three chargers in the CS in the V2G mode. Assuming three EVs in this scenario discharge energy from their batteries to produce the required power for the electricity grid. All the system was modeled and simulated using MATLAB/Simulink in version R2024a.

4 First Operation Mode Simulation Results

4.1 Current waveform distortion

Figure 2, Figure 3 and Figure 4 show CS current waveforms of scenarios one, two and three respectively. The waveforms show that the current will be highly distorted because of harmonics generated by chargers which are considered as non-linear loads.

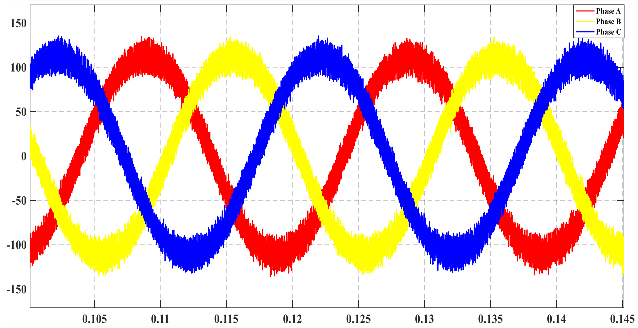

Fig. 2 Current waveform of the CS during scenario one

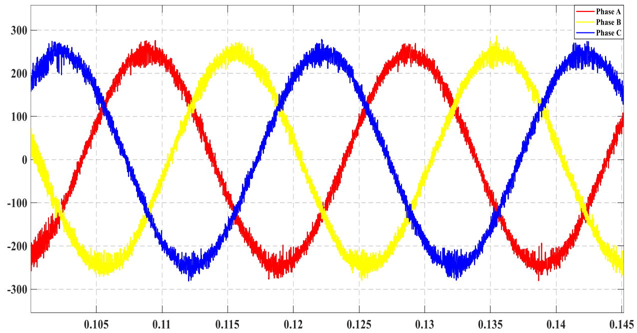

Fig. 3 Current waveform of the CS during scenario two

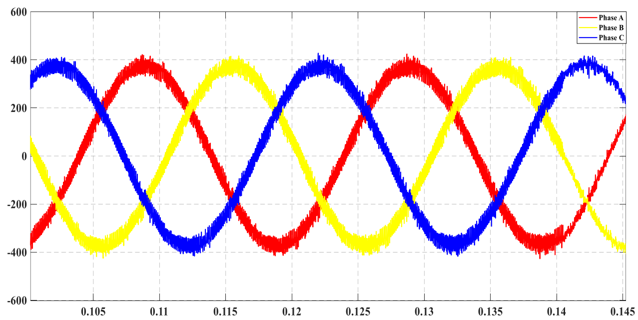

Fig. 4 Current waveform of the CS during scenario three

4.2 Current waveform total harmonics distortion (THD)

Figure 5, Figure 6 and Figure 7 show the CS current waveform spectra for scenarios one, two and three respectively. THD of current waveform has a high value in the three scenarios. The second harmonics which has a frequency of 100 hertz has a very large value, more than 40 percent of the fundamental current waveform, and the third harmonics which has a frequency of 150 hertz is more than 12 percent of the fundamental current waveform. High values of harmonics cause series problems such as increasing conductors' temperature, power losses in cables as well as eddy current losses in transformers and rotating machines [25].

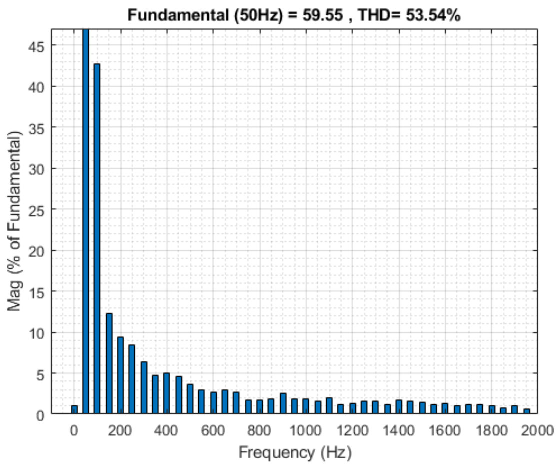

Fig. 5 Current waveform spectrum of the CS during scenario one

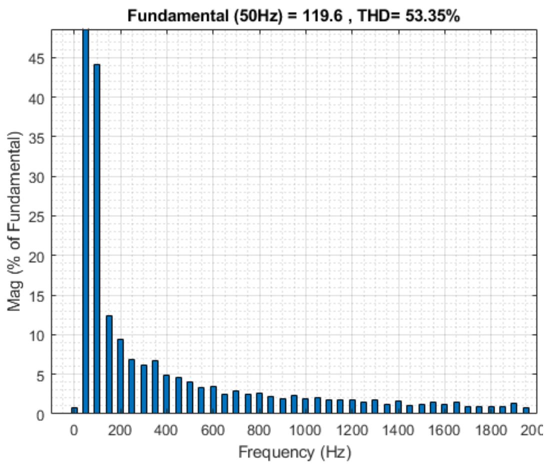

Fig. 6 Current waveform spectrum of the CS during scenario two

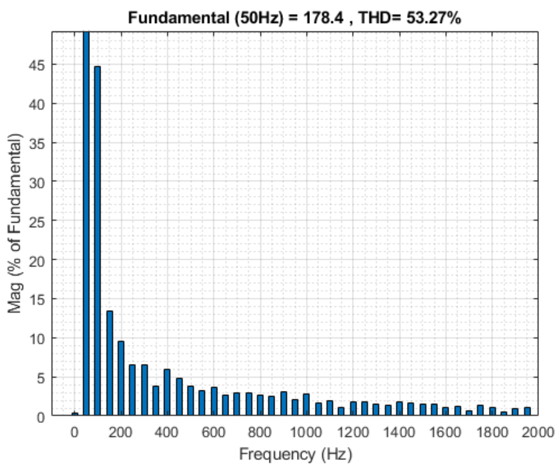

Fig. 7 Current waveform spectrum of the CS during scenario three

4.3 Voltage waveform total harmonics distortion

Figure 8, Figure 9 and Figure 10 show voltage waveform spectra of scenarios one, two and three respectively. THD of voltage waveform has a small value in the three scenarios. It reaches its maximum value 2% in the third scenario because of the high current value and high voltage drop so that a high voltage distortion [26]. No load losses of the DT increase with increasing of voltage harmonics [27].

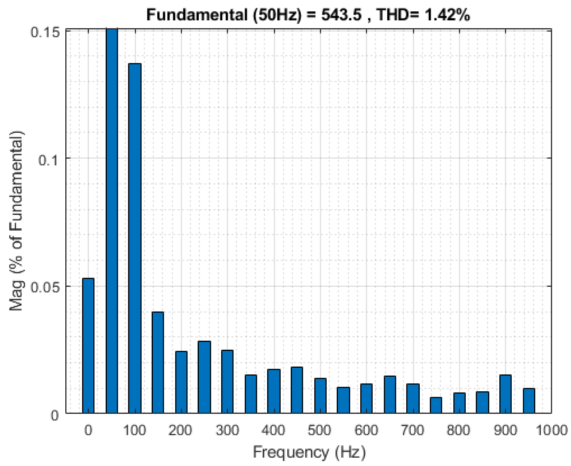

Fig. 8 Voltage waveform spectrum across the CS during scenario one

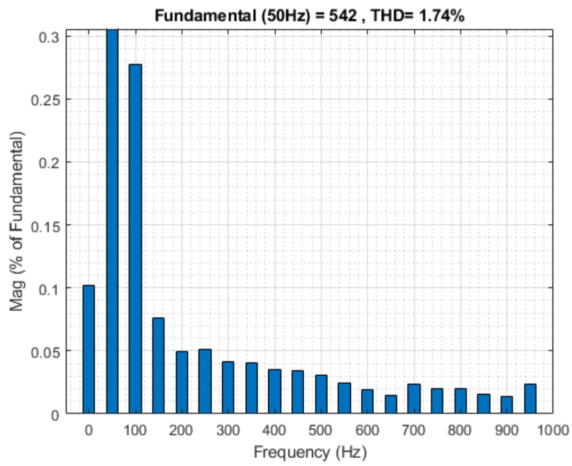

Fig. 9 Voltage waveform spectrum across the CS during scenario two

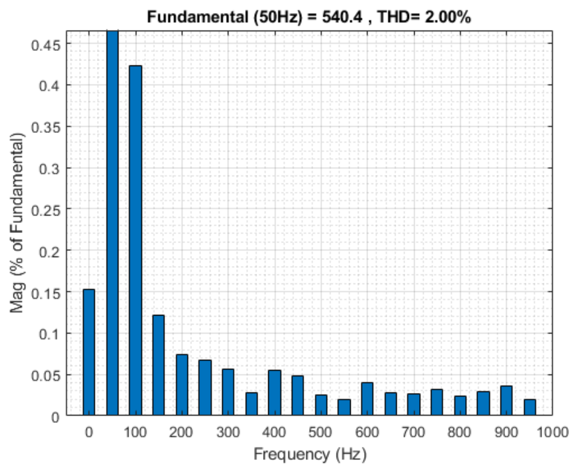

Fig. 10 Voltage waveform spectrum across the CS during scenario three

5 Enhancement of DC Fast Charging Impacts

As per the institute of Electrical and Electronics Engineers (IEEE) 519 standard, THD for voltage must not exceed 8% in low voltage systems with a voltage not exceeding 1000 V [28]. **Table 2** shows IEEE-519 standard limits for the distortion in voltage waveform [29].

Table 2 IEEE-519 voltage THD limits

System voltage	Individual harmonics (%)	THD (%)
V ≤ 1000 V	5.0	8.0
1000 V < V ≤ 69 kV	3.0	5.0
69 kV < V ≤ 161 kV	1.5	2.5
161 kV < V	1.0	1.5

Table 3 shows current harmonic distortion as per the IEEE 519 standard [29]. The standard value of THD is according to the ratio between rated short circuit current and the maximum demand current for the load (I_{sc} / I_L) [28].

Table 3 IEEE-519 current THD limits

I_{sc} / I_L	Order of individual harmonics					
	h < 11	11 ≤ h < 17	17 ≤ h < 23	23 ≤ h < 35	35 ≤ h	THD (%)
< 20	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 10^2	10.0	4.5	4.0	1.5	0.7	12.0
10^2 < 10^3	12.0	5.5	5.0	2.0	1.0	15.0
> 10^3	15.0	7.0	6.0	2.5	1.4	20.0

From studied model simulation results, it's clear that scenario three is the worst-case scenario while the three fast chargers are operated. Enhancing impacts of DC CSs in the electricity grid is done by adding a series inductive inductance with any CS so that the topology of the CS becomes as shown in **Fig. 11**

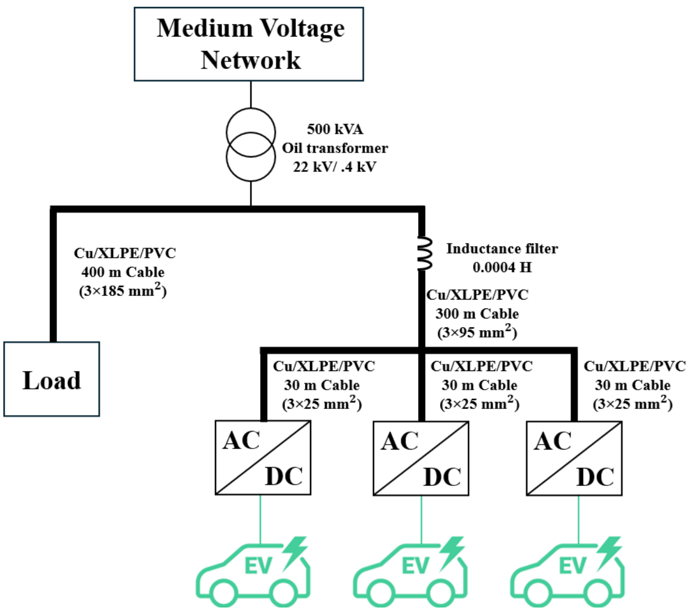

Fig. 11 The proposed topology of the charging station after adding the filter

The inductive reactance acts as filter by reducing the value of THD in current and voltage waveforms. **Figure 12** and **Figure 13** show the spectrum of current and voltage waveforms, respectively after adding the filter and considering the worst-case scenario. THD in current waveform is reduced from 53.27% to 1.58%. Current components which have different frequencies from the fundamental frequency have a magnitude of less than 0.8% of current fundamental frequency. Also, THD in voltage waveform is reduced from 2% to 0.15%. Components which have different frequencies from the fundamental frequency have a magnitude less than 0.025% of voltage fundamental frequency.

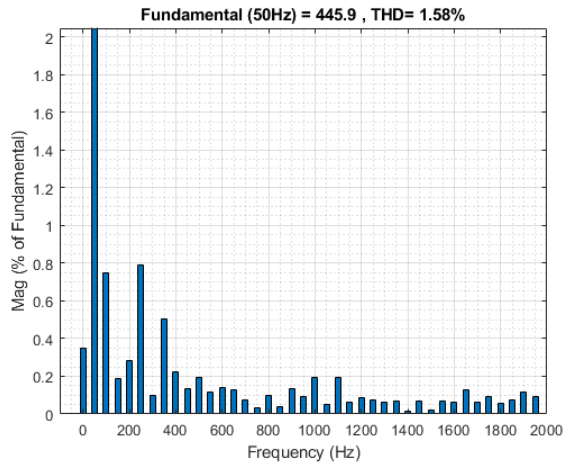

Fig. 12 Spectrum of the CS current waveform after adding the proposed filter considering the worst-case scenario

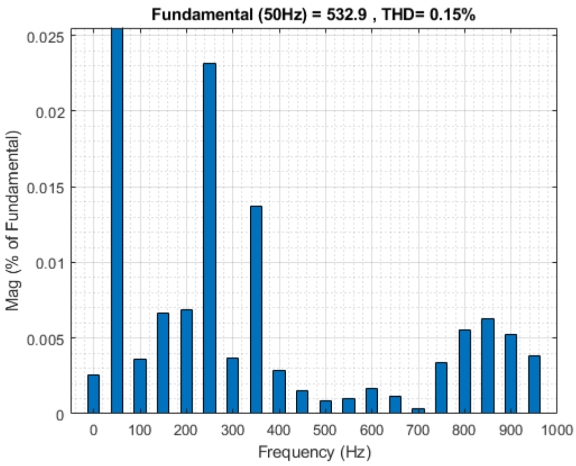

Fig. 13 Spectrum of voltage waveform across the CS after adding the proposed filter considering the worst-case scenario

The current waveform of the CS considering worst case scenario becomes nearly sinusoidal, and the distortion is significantly reduced. **Figure 14** shows the current waveform of the CS during worst case scenario after adding the proposed filter. Enhancing the performance of CS and reducing its negative impacts during the worst-case scenario means that the other two scenarios will have a small value of THD for current and voltage waveforms. Also, waveforms will have less distortion. Reducing harmonics number generated by CS achieves many advantages such as reducing the neutral current, which is caused by third harmonics, improving overall efficiency of the system, reducing overheating of electrical equipment [30]. By reducing harmonics, false operation of protective relays is reduced and the interfacing between power with communication lines is mitigated [31].

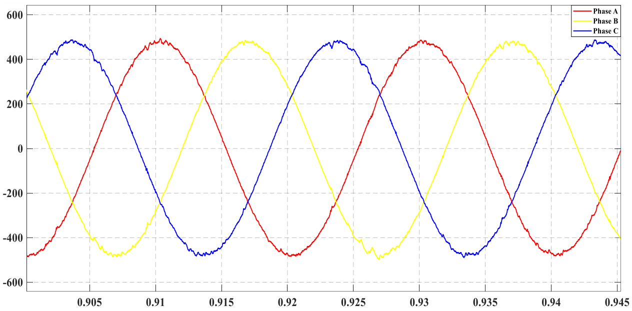

Fig. 14 Current waveform of the CS after using the proposed filter considering the worst-case scenario

Figure 15 and **Figure 16** show short circuit current on CS waveforms without and with the filter respectively. The instantaneous value of short circuit current without the filter reaches a value of more than 3000 A. With the filter maximum instantaneous value of the short circuit current does not reach 1000 A. As a result, the filter reduces the short circuit current from 2750A root mean square (RMS) value to 750A RMS value. Reducing the short circuit current level on the CS is very useful as the rating of equipment such as circuit breakers, cables and switchgears will be selected depending on the new reduced value which decreases the cost rapidly.

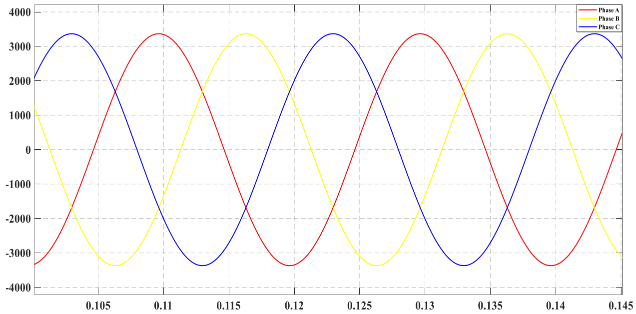

Fig. 15 Short circuit current waveform of the CS without using the proposed filter

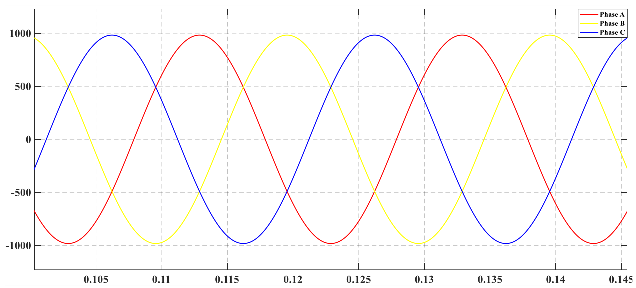

Fig. 16 Short circuit current waveform of the CS after using the proposed filter

6 Vehicle to Grid Operation Mode

In second mode, The CS is operated in V2G mode which represents the fourth scenario. Operating the CS in V2G mode without using the proposed filter would lead to the same disadvantages of the last three scenarios in operation mode one. A very high distortion will appear in current wave form as shown in **Fig. 17.** Also, a very high distortion will appear in voltage waveform. THD of current and voltage waveforms will be a high value.

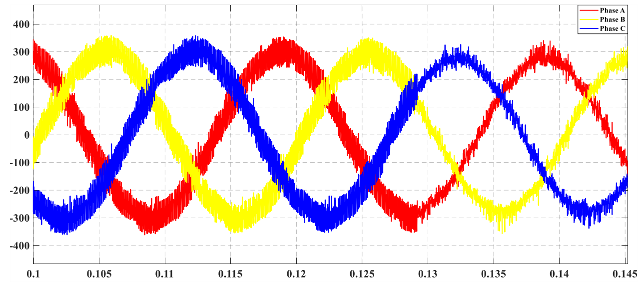

Fig. 17 Current waveform in V2G mode without the proposed filter

It seems that the high value of THD in current or voltage represents a big problem in V2G because the power is injected directly into the grid. All these distortions will appear on the grid and defect other loads. The filter for the CS in this second mode plays an important role in enhancing all the CS impacts. **Figure 18** shows the CS current waveform after using the proposed filter which leads to reducing the distortion and current waveform THD value.

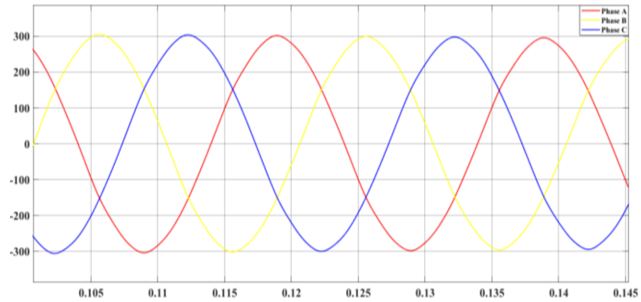

Fig. 18 Current waveform in V2G mode after using the proposed filter

7 Conclusion and Future Work

An actual CS in electricity distribution network of Egypt is modeled and simulated using MATLAB/Simulink. Three scenarios are presented for the CS to study various effects of EVs charging. Additionally, the study includes the V2G operation mode and its effects on the fourth mode. The paper focuses on the negative impacts of CSs on electricity networks.

The results showed that CS injects high values of harmonics in the electricity grid. The distortion of waveforms due to CSs occurs in both voltage and current waveforms. THD in current waveform reaches about 53 % with three 40 kW fast DC chargers operating in case of full power operation. THD in voltage waveform reaches 2% while the three charges operate. Adding an inductive reactance in series with CS as a filter helps in mitigating negative impacts of CS on electricity grid. The filter reduces the THD of the CS's current waveform to 1.58%. Also, filter reduces THD of voltage waveform across the CS to 0.15%. Not only enhancing the value of THD of current and voltage waveforms but also filter reduces the short circuit level on the CS. The short circuit current is reduced from 2750A to 750A by adding the series filter.

For future work, the study will be expanded to include the effects of DC fast charging station on the medium voltage network. Also, the study may include new aspects of the problem such as solving the problem of increasing power demand due to high power of the CSs. Finally, the new study will include the effect of V2G mode on the power system stability.

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