LCL Filter Design and Simulation for Vehicle-To-Grid (V2G) Applications

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Abstract. There is a remarkable increase in the number of electric vehicles (EV) with the increase in the demand for renewable energy sources. The integration of EVs into the grid has become an important issue with the widespread use of EVs. The grid integration of EVs has detrimental effects on power quality. The charging topologies such as vehicle-to-grid energy transfer (V2G), grid-to-vehicle energy transfer (G2V), vehicle-to-vehicle energy transfer (V2V) have been developed in order to overcome this problem. In this study, a microgrid using V2G and G2V topologies has been designed for a building and the EVs in this building. In this designed microgrid, 120 kw energy flow is provided for the loads in the building and the charging of EVs. When an extra load is added to the grid in the building, the energy above 120 kw is supplied from the EVs in the microgrid (V2G) to support the grid. The LCL filter design has been carried out for the grid connected inverter used in the V2G topology in the microgrid. After determining the output power, switching frequency, busbar voltage, etc. values of the three-phase inverter for the designed V2G topology, the LCL filter parameters have been calculated. The total harmonic distortion (THD) has been determined according to the calculated parameter values. It has been observed that the THD performance of the LCL filter is better than the THD performance of the LC and L filters. The designed microgrid simulations and LCL filter analyses have been carried out in the MATLAB 2020b Simulink program. With the simulations, G2V and V2G topologies have been analysed and LCL filter design has been carried out for the grid connected inverter used in the V2G topology.

Keywords: LCL Filter · V2G · G2V · Smart Grid

1 Introduction

The demand for renewable energy sources is increasing day by day, and there is a remarkable increase in the number of electric vehicles (EV) with the increasing use of renewable energy sources. As this remarkable increase will disrupt the supply-demand balance, the integration of EVs into the grid has become an important issue. The integration of EVs into the grid will place unpredictable over loads on the existing grid. The studies have

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been carried out in recent years in order to overcome this network capacity problem. The charging topologies such as vehicle-to-grid energy transfer (V2G), grid-to-vehicle energy transfer (G2V), vehicle-to-vehicle energy transfer (V2V) have been developed with the studies carried out [1].

In the V2G topology, when there is a power demand above the power capacity of the grid to which the EV is connected, this demand is supplied from the EV group which connected to the grid. The demand for three-phase grid-connected inverters with pulse width modulation (PWM) that control for grid connection and power control of EVs has been increasing in recent years [2, 3]. The harmonics occur due to the switching elements in the inverters which used for the connection of EVs to the grid [4]. The total harmonic distortion (THD) value of the fundamental frequency current transferred to the grid in grid-connected inverters must comply with international standards [5]. A filter must be used at the output of the inverter in order to transfer the current to the grid by complying with these standards. There are many filtering methods for grid-connected inverters. The most commonly used filter type is the LCL filter. The design of the LCL filter is smaller than other filters and it has lower cost. But the determining the parameters of the LCL filter is more complicated. Therefore, the parameters must be accurately calculated and analysed in order for the system to remain in a steady state. The LCL filter parameters should be calculated by determining the output power, switching frequency, busbar voltage, etc. values of the designed three-phase inverter [6].

In this study, a microgrid which consisting of a building and EVs and which using V2G and G2V topologies is designed. In this designed microgrid, 120 kW energy flow is provided for the loads in the building and the charging of the EVs. When an extra load is added to the microgrid inside the building, more than 120 kW of energy is provided from the electric vehicles in the grid to support the grid. In other words, V2G topology is operated. In this study, the filter design has been carried out for grid connected inverters that used in V2G topology. According to the determined parameter values, THD performance of LCL filter has been shown to be better by comparing it with LC and L filters. The G2V and V2G topologies have been examined with the simulations and The LCL filter design has been carried out for the grid connected inverter that used in the V2G topology.

2 EV Charge Topologies

The charge topologies have three components. The first of these components is the current conventional grid. This grid is our main energy source. The other component is the batteries of the EVs. The batteries are other energy source that can store energy. The third component is the energy management system that controls the energy flow between these two energy sources. The different charging topologies have been developed by using these three components. These topologies are G2V, V2G and V2V (Fig. 1). With these topologies, the bidirectional energy flow is carried out.

The charging stations are becoming more widespread and the charging units are set up in the car parks of the owners' homes with the increase in the use of EVs. At these charging stations and parking lots, the current conventional grid is used to charge the batteries of the EVs. This topology is called G2V.

With the development of control methods, the bidirectional energy flow control is carried out in AC and DC grid [7, 8]. The parking lot or charging station where EVs charge would act as a microgrid. When there is a distortion in power quality or an increase in demand in this microgrid, the batteries of the vehicles connected to the microgrid would provide energy to the microgrid with independent inverters (DC to AC). This topology is called V2G.

As the smart grid perspective develops, the vehicles in the same microgrid use each other's batteries to charge their batteries (V2V topology) [1].

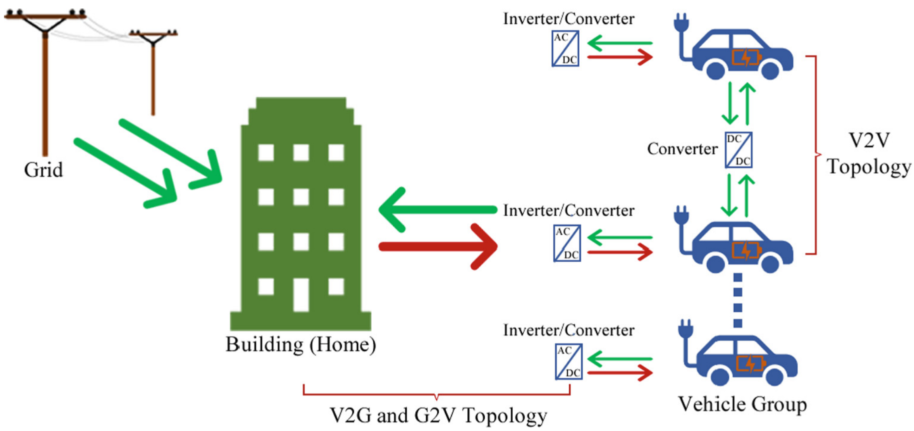

Fig. 1. EV Charge Topologies

3 Basic Power Filters

The power quality of the inverter output is very important in the V2G topology. The signal at the inverter output contains harmonics at different levels due to the frequency of the switching signal. For this reason, the use of filters at the inverter output is necessary [6, 9]. The filter types L, LC and LCL (Fig. 2) are used in grid-connect inverters. The most commonly used filter in grid-connected inverters is the L filter. It must have a high inductance value to reduce current ripple. For this reason, the dimensions of the L filter are very large, so the cost is also high [10]. In order to reduce the larger dimensions of the L filter, the LC filter that another filter type is used. In the LC Filter, the resonance frequency is not constant due to the uncertainty of the grid inductance. Therefore, the LC filter is not suitable for grid-connected inverters [10–12]. The LCL filters have a higher harmonic suppression ratio [12]. The harmonics negatively affect the network and the loads in the system. Also, it could even cause serious damage. According to IEEE-519 harmonic standards; The THD value of the current drawn from the grid should be less than 5% [12–14]. The switching frequency of the inverters is greatly reduced by using the LCL filter. LCL filter could be designed with a smaller dimension, so cost savings could also achieve [12].

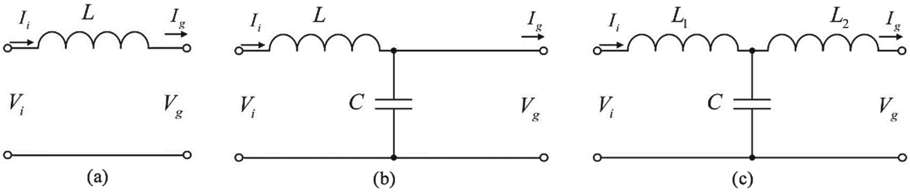

Fig. 2. Basic Power Filters: (a) L Filter (b) LC Filter (c) LCL Filter

3.1 LCL Filter Design

The LCL filter has been designed for the three-phase grid-connected inverter in V2G topology (Fig. 3). The LCL filter could suppress high-order harmonics at its output. But the design should be done very carefully. The incorrect design values could cause increased distortion at the filter output. Therefore, LCL filter should be designed with appropriate values.

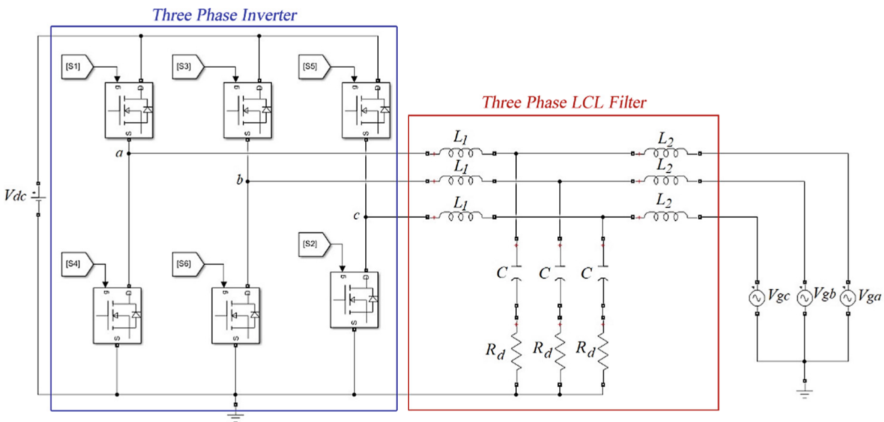

Fig. 3. Three-Phase Grid-Connected Inverter with LCL Filter

The transfer function of LCL filter is given in Eq. 1.

$$\frac{I_g(S)}{V_i(S)} = \frac{1}{(L_1L_2C)S^3 + (R_1L_2C + R_2L_1C)S^2 + (R_1R_2C + L_1 + L_2)S + (R_1 + R_2)} \quad (1)$$

In LCL filter design, the resonant frequency should be far from the mains frequency. The resonance frequency of the LCL Filter is calculated as in Eq. 2.

$$f_r = \frac{1}{2\pi}\sqrt{\frac{L_1 + L_2}{L_1L_2C}} \quad (2)$$

The performance of the LCL filter is affected by the selected resonance frequency, the value of the capacitor C, and the inductance values of the L1 and L2 coils. For this reason, Eq. 3 should be considered in the selection of the resonant frequency.

$$10f_g \leq f_r \leq (f_{sw}/2) \tag{3}$$

The reactive power requirements can cause resonance of the capacitor interacting with the grid. Therefore, passive or active damping must be added by including a resistor in series with the capacitor. The passive damping solution is chosen in this study, but active solutions could also be applied [14, 15]. The value of the damping resistor (R_d) connected in series with the filter capacitor could be calculated as follows:

$$R_d = \frac{1}{3w_r C} \tag{4}$$

In order to perform the filter design, the following parameters have to be known:

Vn: Line to Line RMS Voltage at the inverter output
Vp: Phase voltage at the inverter output
Pn: Nominal Active Power
Vd: DC line voltage
fg: Grid Frequency
fsw: Switching Frequency
fr: Resonance Frequency

Filter values are obtained by using base values [14]:

$$Z_b = \frac{V_n^2}{P_n} \tag{5}$$

$$C_b = \frac{1}{w_g Z_b} \tag{6}$$

Z_b*: Base Impedance*
C_b*: Base Capacitance*

During the design of the filter capacitance, the power correction factor was considered to be a maximum of 5%. This calculated value corresponds to 5% of the base capacity value.

$$C = 0.05C_b \tag{7}$$

The maximum amount of ripple in the current at the inverter output is given in Eq. 8.

$$\Delta I_{Lmax} = \frac{2V_{DC}}{3L_1}(1-m)mT_{sw} \tag{8}$$

T_{sw}*: Switching time of the inverter*
m: Modulation factor of the inverter

It is seen that the highest peak-to-peak current harmonic occurs at m = 0,5. The maximum amount of ripple of the inductance current is given in Eq. 12.

$$\Delta I_{Lmax} = \frac{V_{DC}}{6f_{sw}L_1} \tag{9}$$

L_1 is the inductance on the inverter side. The 10% ripple in current is considered for the maximum nominal current. The maximum nominal current is shown in Eq. 10.

$$\Delta I_{Lmax} = 0.1I_{max} \tag{10}$$

$$I_{max} = \frac{P_n\sqrt{2}}{V_p} \tag{11}$$

With these equations, the L1 value is calculated as in Eq. 12.

$$L_1 = \frac{V_{dc}}{6f_{sw}\Delta I_{Lmax}} \tag{12}$$

The LCL filter equivalent circuit is analysed as a current source to calculate the ripple reduction for each harmonic frequency. The LCL filter limits its own value to 20% to reduce the expected 10% current ripple and creates a 2% ripple in the output current [15, 16]. The relation between the harmonic current of the inverter and the grid and the simplified version of this relation are given in Eq. 13.

$$\frac{i_g}{i_i} = \frac{1}{\left|1 + r\left|1 - L_1C_bw_{sw}^2x\right|\right|} = k_a \tag{13}$$

The inductance value (L_2) on the grid side can be calculated by using the k_a value obtained in Eq. 13.

$$L_2 = \frac{\sqrt{\frac{1}{k_a^2}} + 1}{C_f w_{sw}^2} \tag{14}$$

The constant *ka* in Eq. 13 and 14 is expressed as the desired reduction ratio. Displayed as $C = 0.01 / 0.05Cb$.

The constant r is defined as the ratio of the inductances on the grid and inverter side to each other. In this case, the resulting equation is given in Eq. 15.

$$L_2 = rL_1 \tag{15}$$

3.2 Simulation and Analysis Results

Three-phase grid-connected inverter model used in V2G topology (Fig. 4) has been designed in MATLAB 2020b/Simulink program. The Grid values and LCL filter values for the simulation of the designed model are given in Table 1. The simulations of the model have been performed using these values as a reference.

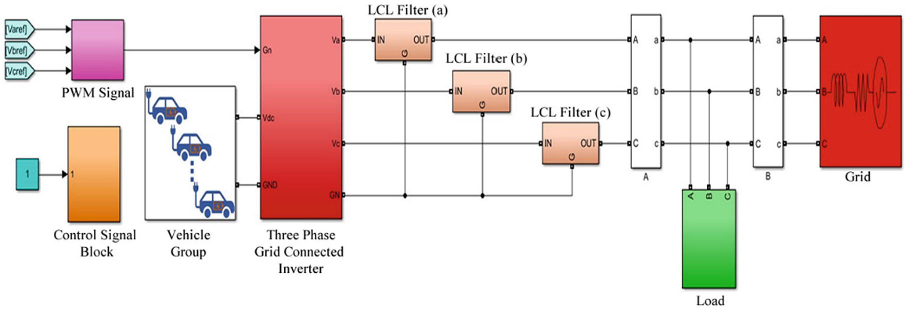

Fig. 4. Three-Phase Grid-Connected Inverter Model used V2G Topology

As it is known, the inverter has a DC signal at its input and an AC signal at its output. The output signal of the inverter has to be a pure sine wave. But the output voltage of an inverter contains harmonics and ripple in practice. These ripples and harmonics are suppressed using the filter. In addition, the phase angles of the grid and the inverter output voltages and currents must overlap in grid-connected inverters. By using the filter, the phase angles of the inverter signal and the grid signal are overlapped in a short time. The three-phase V-I (Voltage-Current) graph of the grid-connected inverter is given in Fig. 5. In Fig. 5a, the V-I graph of the grid-connected inverter with filter is given. As seen in Fig. 5a, harmonics have been suppressed and phase angles have been adjusted. The simulation has been repeated without the filter and the unfiltered V-I graph is given in Fig. 5b. In the current graph, it is seen that the phase angles do not overlap and there are harmonics.

The grid has a total energy of 120 kW in the simulation model. It feeds a load with 75 kW of this energy and charges the EVs in the charging station with 45 kW of it. Here, the G2V topology is operated. A second load of 100 kW is connected to the grid. The V2G topology is starting to operate since the grid cannot supply the demanded 175 kW of energy. The 55 kW energy portion (175 kW–120 kW = 55 kW) required by the grid is provided from the batteries of the EVs in the charging station.

Table 1. System Parameters

fg	Grid Frequency	50 Hz
f_s	Switching Frequency	10 kHz
V_g	Grid Voltage	380 V
V_{dc}	DC Link (Battery) Voltage	800 V
L_1	Inverter Side Inductor of LCL Filter	1 mH
L_2	Grid Side Inductor of LCL Filter	500 μH
C	Capacitor of LCL Filter	100 μf
R_d	Damping Resistor	10 Ω

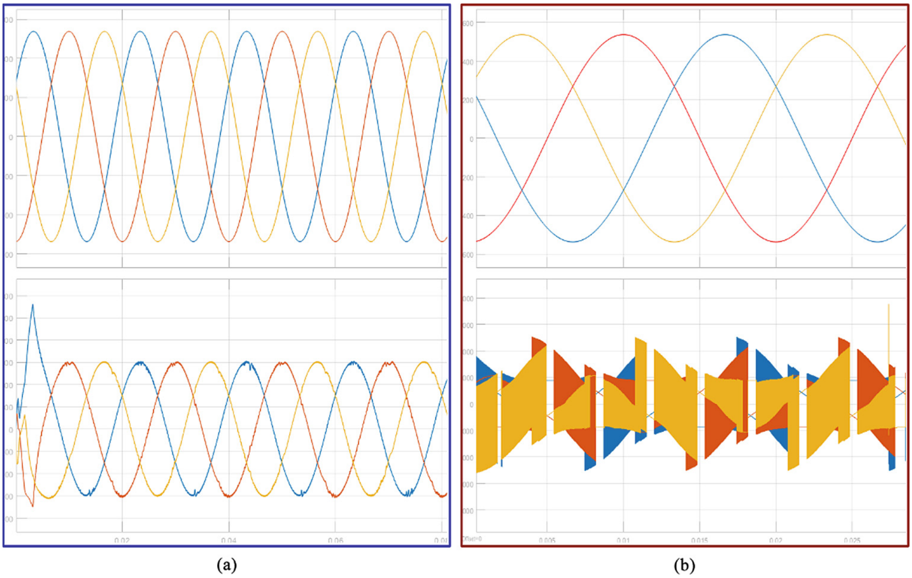

Fig. 5. Three-Phase V-I Graph a) with LCL Filter b) without Filter

In Fig. 6, the energy flow graph of the grid is given. In Fig. 7, the energy flow graph of EVs is given. EVs charge their batteries by getting 45 kW of energy from the grid in the G2V topology. During the V2G topology, EVs provide 55 kW of energy support to the grid for feeding a total of 175 kW of load.

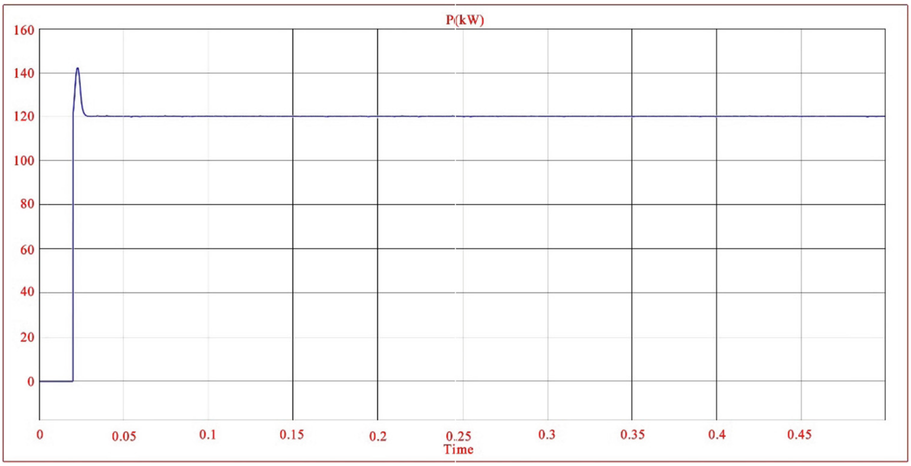

Fig. 6. Energy Flow Graph of the Grid

In the three-phase grid-connected inverter model used for the V2G topology, simulations have been performed for L, LC, LCL filters, respectively, and THD values have

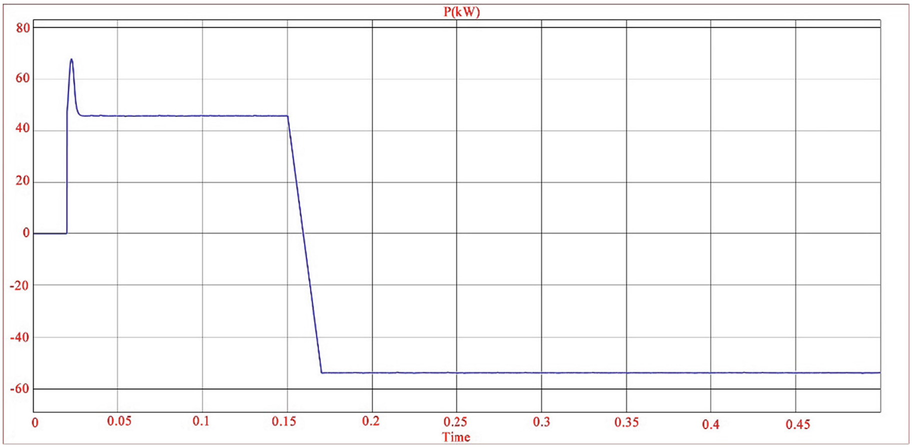

Fig. 7. Energy Flow Graph of EV Battery Group

been measured. According to IEEE-519 harmonic standards; It has been emphasized that the THD value of the current drawn from the grid should be less than 5%. THD value is less than 5% for all three filters. FFT analyses have been performed for L, LC, LCL filters, respectively, and the results are given in Fig. 8, Fig. 9 and Fig. 10.

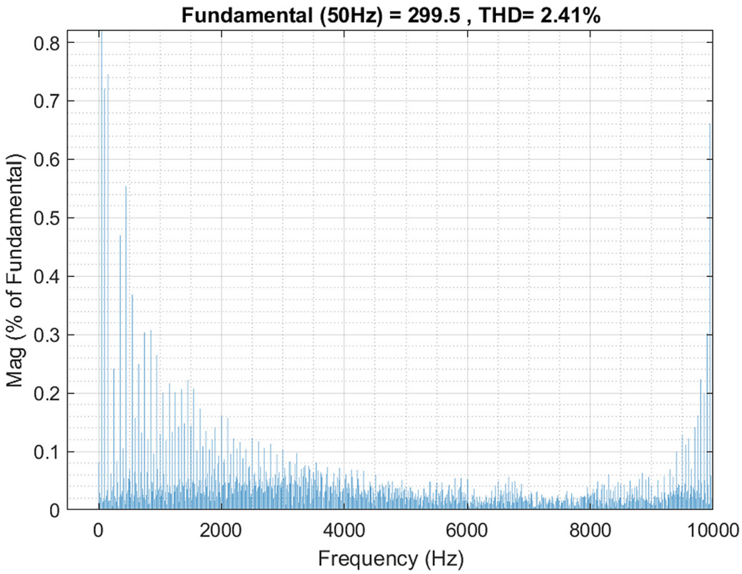

Fig. 8. L Filter FFT Analysis

THD values for L, LC, LCL filters have been measured as 2.41%, 2.38% and 1.52%, respectively when looking at the results of the FFT analysis. It is seen that the LCL filter gives better results than the others. Also, the FFT analysis of the simulation has

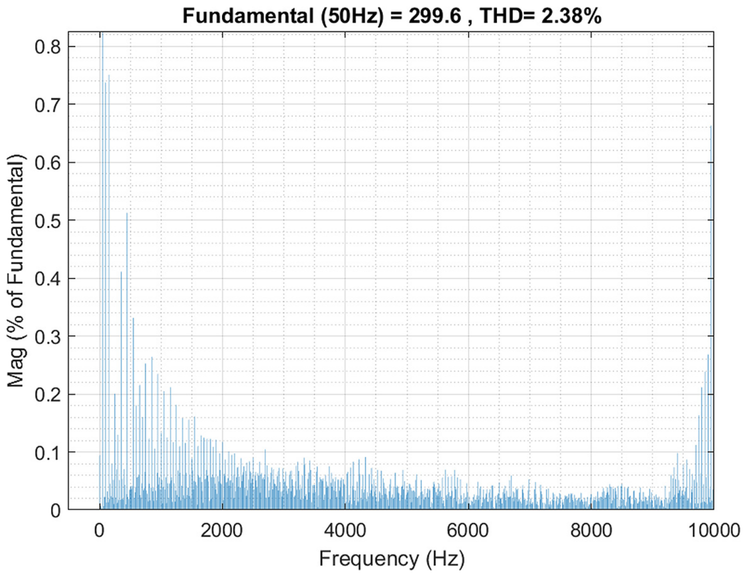

Fig. 9. LC Filter FFT Analysis

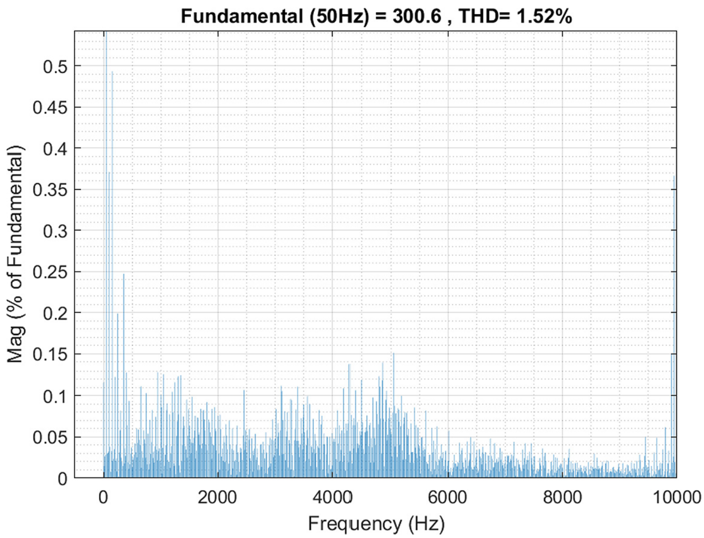

Fig. 10. LCL Filter FFT Analysis

been performed by removing the filter from the designed three-phase grid-connected inverter. In the FFT analysis, the THD value has been measured as 1038.28% (Fig. 11). According to this result, the necessity of using filters is seen.

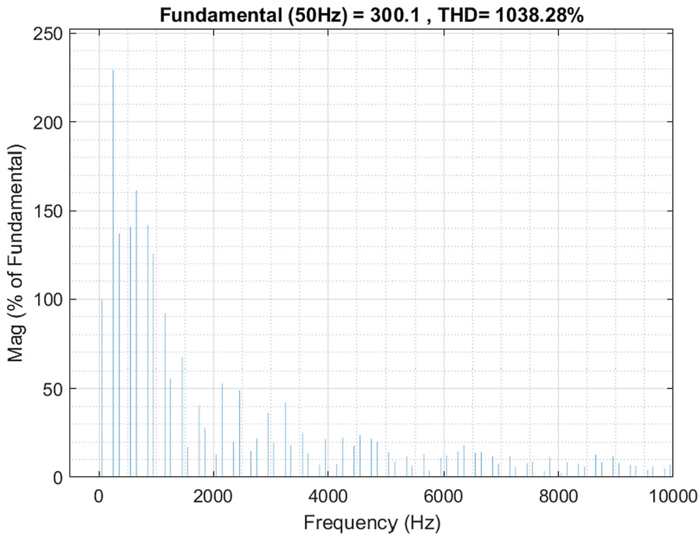

Fig. 11. FFT Analysis without Filter

4 Conclusion

The number of electric vehicles is increasing day by day. This increase disrupts the supply-demand balance in the existing electricity grid. For this reason, the demand for renewable energy sources is also increasing. In order to offer a solution to this problem, charging topologies such as vehicle-to-grid energy transfer (V2G), grid-to-vehicle energy transfer (G2V), vehicle-to-vehicle energy transfer (V2V) have been developed. These topologies are foreseen to support renewable energy sources. V2G topology has been studied in this paper. V2G topology has been used to support the micro-grid in the current grid.

Inverters are used to connect EVs to the grid. The filter at the output of the inverter gains importance in order to suppress the harmonics caused by the switching elements. In this paper, grid-connected inverter filters which are used in V2G topology have been studied. The design of the LCL filter has been explained. it has been shown that the LCL filter is more efficient with the simulation results. The THD value of the fundamental frequency current transferred to the grid in grid-connected inverters should be below 5% according to international standards. According to the simulation results of the designed system, THD value for L, LC, LCL filters has been measured as 2.41%, 2.38% and 1.52%, respectively. The suggested model has been found to be efficient with the simulation results. The power quality at the inverter output of the designed model has been significantly improved with LCL filter.

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