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Bidirectional DC-DC Converter and Single-Phase Grid-Connected Inverter Design for Energy Management in V2G Topology

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Submitted: 06.05.2024 Revised: 04.06.2024 Accepted: 27.06.2024 doi:10.30855/gmbd.0705A16

Keywords: V2G, Grid-Connected Inverter, Bidirectional DC-DC Converter, Micro Grid, EV

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ABSTRACT

As renewable energy resources dwindle and the world's population grows, the balance between energy supply and demand is being adversely affected. The rapid increase in the number of EVs causes power quality problems in existing conventional grids. Topologies such as V2G, G2V, and V2H are being studied in order to overcome these problems. In this study, a microgrid is designed for power flow in single-phase V2G topology. In this microgrid, there is one EV, one home, and one PV panel. The EV is charged by the PV panel during the daytime when it is in the parking lot. When there is a power quality problem in the microgrid, the V2G topology is activated and power flows from the EV battery to the grid. A single-phase grid-connected inverter and a bidirectional DC-DC converter were designed to operate this system. The simulations of the designed microgrid were performed in the MATLAB/Simulink program. According to the simulation results, installing this system in homes or workplaces with EVs, charging the EV battery with PV panel, and using the EV battery to eliminate power quality problems that may occur in the existing microgrid provides a solution for single-phase V2G topology.

V2G Topolojisinde Enerji Yönetimi için Çift Yönlü DC-DC Dönüştürücü ve Tek Fazlı Şebeke Bağlantılı Evirici Tasarımı

ÖZ

Yenilenebilir enerji kaynaklarının azalması ve dünya nüfusunun artmasıyla birlikte enerji arz talep dengesi olumsuz etkilenmekte. EV sayısının hızla arması mevcut konvansiyonel şebekelerde güç kalitesi problemlerine neden olmaktadır. Bu problemlerin üstesinden gelebilmek için V2G, G2V ev V2H gibi topolojilerde çalışmalar yapılmaktadır. Bu çalışmada tek fazlı V2G topolojisinde güç akışı için bir mikro şebeke tasarlandı. Bu mikro şebeke içerisinde bir adet EV, bir adet ev ve bir adet PV panel bulunmaktadır. EV gündüzleri otoparkta iken PV panel ile şarj olmaktadır. Mikro şebekede güç kalitesinde bir problem olduğunda ise V2G topolojisi işletilerek EV bataryasından şebekeye güç akışı gerçekleştirilmektedir. Bu sistemin işletilebilmesi için bir adet tek faz şebeke bağlantılı evirici ve bir adet çift yönlü DC-DC dönüştürücü tasarımı gerçekleştirilmiştir. Tasarlanan mikro şebekenin simülasyonları MATLAB/Simulink programında yapılmıştır. Simülasyon sonuçlarına göre EV bulunan evlerde ya da iş yerlerinde bu sistem kurularak PV panel ile EV bataryasının şarj edilmesi ve EV bataryasının mevcut mikro şebekede oluşabilecek güç kalitesi problemlerinin giderilmesinde kullanılması tek fazlı V2G topolojisi için bir çözüm önerisi sunmaktadır.

Anahtar Kelimeler: V2G, Şebeke Bağlantılı Evirici, Çift Yönlü DC-DC Dönüştürücü, Mikro Şebeke, EV

To cite this article: S. Yildiz and H. H. Sayan, “Bidirectional DC-DC Converter and Single-Phase Grid-Connected Inverter Design for Energy Management in V2G Topology,” *Gazi Journal of Engineering Sciences,* vol.10, no.2, pp. 419-431, 2024. doi:10.30855/gmbd.0705A16

1. Introduction

There has been a remarkably rapid increase in the use of electric vehicles (EVs) in parallel with the growth in demand for energy resources worldwide. This rapid increase is disrupting the supply-demand balance and makes grid integration of EVs an important issue. This rapid increase in the number of EVs adds unpredictable large loads to the grid during grid integration. These unpredictable loads cause power quality issues such as frequency instability, voltage fluctuations, charging harmonics, and unbalanced loads on the grid. Energy flow topologies such as Vehicle-to-Grid (V2G), Grid-to-Vehicle (G2V), Vehicle-to-Vehicle (V2V), and Vehicle-to-Home (V2H) have been developed in recent studies to overcome this grid capacity problem [1,2]. The main elements in these topologies are the existing conventional grid, the microgrid within the vehicle batteries, and renewable energy sources such as photovoltaic (PV) panels, battery energy storage systems (BESS), wind turbines, etc. (Figure 1). The goal is to maintain power quality by maintaining the supply-demand balance in the existing conventional grid with energy flow topologies that control the existing energy flow using these three basic structures. In the future, as electric vehicles replace today's fossil fuel vehicles, the use of these power flow topologies will become a necessity. In this study, a single-phase V2G topology is realized where energy flows between a conventional grid and a microgrid consisting of a home, an EV, and a PV panel connected to this grid. In the designed system, a single-phase grid-connected inverter is designed for the EV battery to transfer energy to the grid in V2G topology. A bidirectional DC-DC converter (BDC) is designed to charge the EV battery in the microgrid (MG) with the PV panel and provide DC voltage to the grid-connected inverter. The designed topology is simulated and its applicability is demonstrated.

In reviewing the literature, many studies have been conducted on this topic. A study presents the architecture for implementing the V2G-G2V system in a MG using EV level 3 fast charging [3]. In another study, a brief discussion of the evolution of bidirectional conversion in V2G and G2V topology is presented [4]. Another article provides a comprehensive review of bidirectional power factor correction and DC-DC converter topologies for V2G and G2V topologies [5]. The paper in [6] proposes a cascaded interleaved configuration that integrates the PV and utility sources for EV battery charging using inductive power transfer technology in both G2V and V2G topologies. In another paper, the designed MG integrates EV for V2G and G2V operation using solar PV, wind, batteries and grid. The electricity from the DC microgrid with grid, PV, wind and BESS technologies is used to charge EV batteries in G2V topology [7]. In [8], the performance analysis of a grid-connected PV/EV/grid system was performed and the operation was simulated. Another article discusses various BDC topologies used in the V2G system, which can also reduce the cost of charging for electric utilities, thus increasing the profits for EV owners [9]. The paper develops an electric vehicle switched reluctance motor drive powered by a battery/supercapacitor with G2V and V2H/V2G functions [10]. The article [11] investigated the financial benefits of using EVs as temporary energy storage in MG integrated with a PV plant. Another paper proposes an integrated converter with drive, G2V, V2G, and DC/V2V charging capabilities for an EV drive-train using a switched reluctance motor [12]. The paper [13] presents an electric scooter with G2V/V2H/V2G and energy harvesting functions. The paper discusses the design and control of a bidirectional battery charger for EVs, and its operation as an active power filter when connected to the local home electrical grid, and the charger is also designed and controlled in order to operate while charging of the battery from the grid and the injecting the power back to the grid when needed [14]. In study [15] presented the architecture of bidirectional Battery Charger for EVs applications. Another study presents the main operation modes for an EV battery charger in the context of in smart grids and smart homes, i.e., present-day and new modes of operation that can be an asset for EV adoption are discussed and proposed [16]. Another study proposes an on-board bidirectional battery charger prototype to allow the G2V, V2G and V2H operation modes for on-board (EV) battery charger with enhanced V2H operation mode [17]. The article presents an off-board bidirectional battery charger for EVs that is designed to perform various tasks beyond simply charging EVs, such as G2V, V2G, and V2H technologies, and also improving the grid power quality [18]. Another paper reviews various operational modes such as V2G, G2V and V2H, issues, and challenges related to integrating the vehicle with the grid [19]. The paper examines the effects of grid disturbances on EV batteries in G2V/V2G and V2H modes [20].

Valuable studies in the literature are cited above. In this study, an MG was designed for energy management. In this MG, there is a home, an EV and a PV panel. A V2G topology is operated in the MG. Energy flow management between the conventional grid and the designed MG was implemented and a single-phase V2G topology was operated. A single-phase grid-connected inverter is designed for the EV battery to transfer energy to the grid in V2G topology in the designed MG. The BDC design was realized to control the DC energy flow between the EV battery and the PV panel, and the DC energy flow between the EV battery and the grid-connected inverter. The applicability of the designed system is demonstrated by simulation in the MATLAB Simulink program. Our paper consists of four sections. In the first section, the designed system is explained and the literature review is made. In the second section, the units of the designed system are explained and the working steps are given. The third section describes the simulation and results of the designed system. In the fourth section, the conclusion is given.

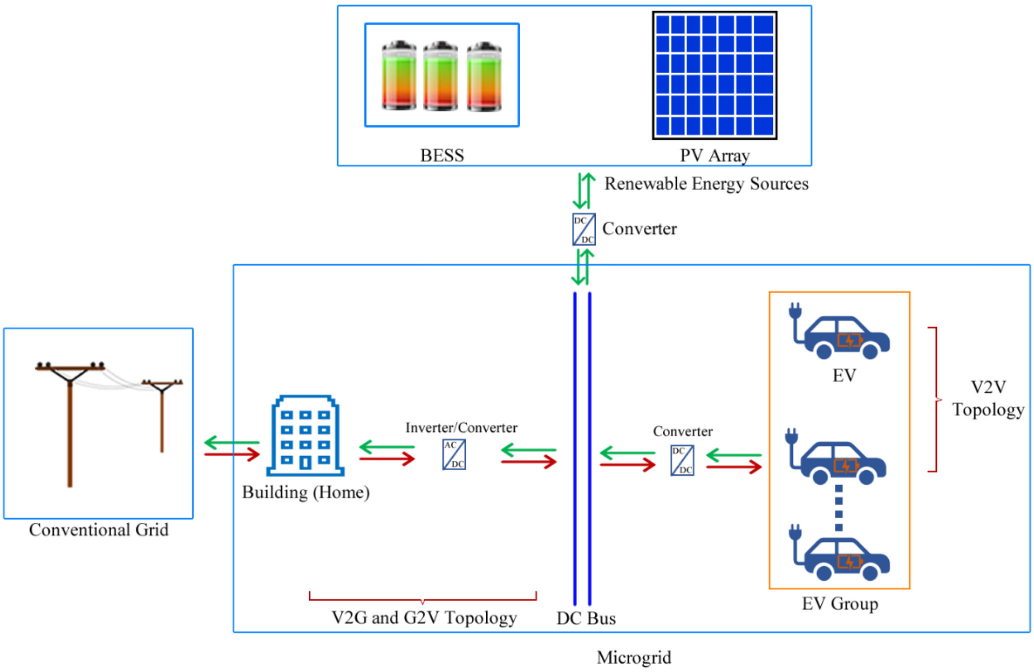

Figure 1. Energy flow topologies between EV and conventional grid

2. Designed V2G Topology

The designed system has four main components: conventional grid, home, EV, and PV panel (Figure 2). Conventional grid is the main energy source. Home, EV and PV panel make up the MG. In the designed MG, the EV battery is charged by the PV panel and the EV battery supplies DC voltage to the grid-connected inverter when the V2G topology is operated. The BDC design is realized to control the energy flow of the EV battery. When the V2G topology is operated, the DC voltage provided by the EV battery is transferred to the grid by the designed single-phase grid-connected inverter.

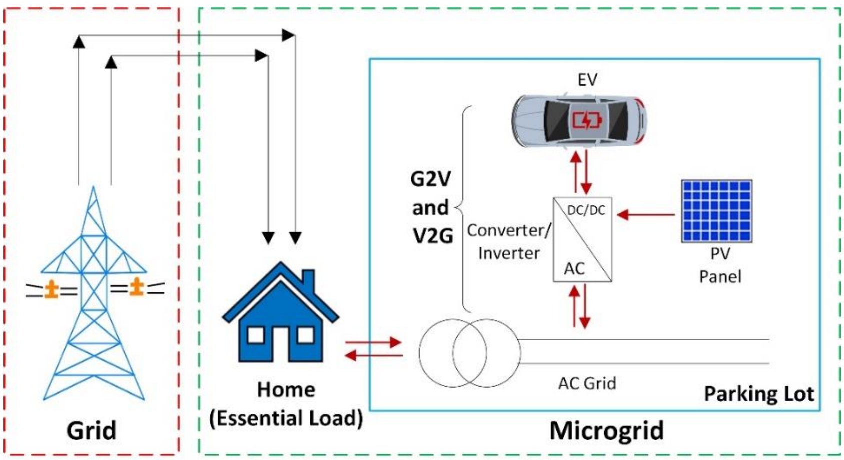

Figure 2. The designed system and components

2.1. Bidirectional DC-DC converter

The main purpose of the BDC (Figure 3) is to enable energy flow between two different DC voltage levels. It has 2 modes, the boost mode and the buck mode. In boost mode, energy flows from the low voltage level to the high voltage level of the boost mode. In buck mode, energy flows from the high voltage level to the low voltage level.

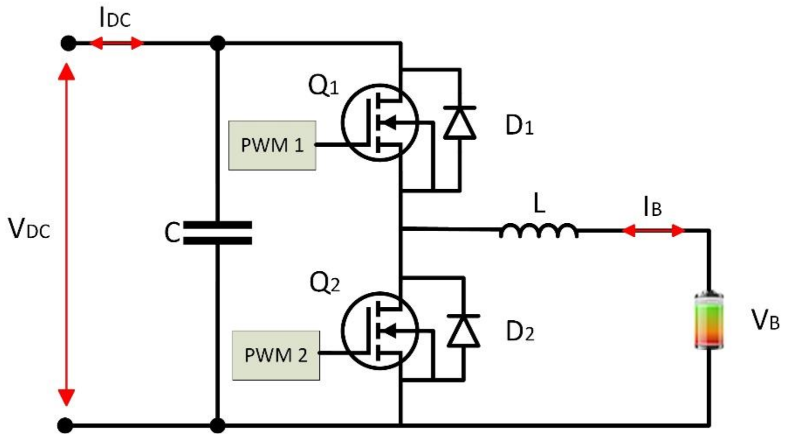

Figure 3. The bidirectional DC-DC converter

In buck mode, energy flows from the high voltage level (V_{DC}) to the low voltage level (V_B) to charge the EV battery with PV. In buck mode, MOSFET Q1 and diode D2 are conducting. The PV is connected to the circuit as the DC power supply, and the EV battery is connected to the circuit as the load and it is charging. EV battery voltage V_B, capacitor (C) and inductor (L) values are calculated as follows [21-23];

$$V_B = V_{DC} \times D_{Buck} \tag{1}$$

$$C_{Buck} = \frac{(1-D_{Buck})V_B}{8L_{Buck}\Delta V_B f_{sw}} \tag{2}$$

$$L_{Buck} = \frac{(V_{DC}-V_B)D_{Buck}}{\Delta I_L f_{sw}} \tag{3}$$

Here;

- V_B : *Battery voltage*
- V_{DC} : *PV voltage in buck mode*
- D_{Buck} : *Transmission rate in buck mode*
- L_{Buck} : *Inductor value in buck mode*
- C_{Buck} : *Capacitor value in buck mode*
- ΔV_B : *Battery voltage ripple.*
- ΔI_L : *Inductor current ripple*
- f_{sw} : *Switching frequency*

In boost mode, the grid-connected inverter is supplied with energy from the low voltage level (V_B) to the high voltage level (V_{DC}). In boost mode, Q2 MOSFET and D1 diode are conducting. The EV battery is connected to the circuit as the DC power supply, and the inverter is connected to the circuit as the load. The EV battery feeds the inverter as a discharge. In boost mode, the inverter input voltage (V_{DC}), capacitor (C) and inductor (L) values are calculated as follows [21-23];

$$V_{Dc} = \frac{V_B}{(1-D_{Boost})} \tag{4}$$

$$C_{Boost} = \frac{D_{Boost}V_{DC}}{R_{out}\Delta V_{DC}f_{sw}} \tag{5}$$

$$L_{Boost} = \frac{V_B D_{Boost}}{\Delta I_L f_{sw}} \tag{6}$$

Here;

- V_B : *Battery Voltage*
- V_{DC} : *Inverter input voltage in boost mode*
- D_{Boost} : *Transmission rate in boost mode*
- L_{Boost} : *Inductor value in boost mode*
- C_{Boost} : *Capacitor value in boost mode*
- R_{out} : *Output impedance in boost mode*
- ΔV_{DC} : *Inverter input voltage ripple.*
- ΔI_L : *Inductor current ripple*
- f_{sw} : *switching frequency*

The BDC operates in two modes, Buck and Boost. *L* and *C* values are calculated separately for these two modes. *L* and *C* values for BDC are determined as follows [22,23];

$$L = max\ (L_{Buck}, L_{Boost}) \tag{7}$$

$$C = max\ (C_{Buck}, C_{Boost}) \tag{8}$$

The pulse width modulation (PWM) signals generated for BDC control are determined according to the reference current (I_{ref}) generated for charging and discharging the EV battery. When the EV battery is charging, I_{ref} is generated by performing PID control with the given reference voltage (V_{ref}) and the instantaneous operating voltage (V_{op}) of the battery (Figure 4-a). When the EV battery is discharging, I_{ref} is generated by performing PID control with the reference voltage (V_{ref}) and the load voltage (V_{Load}) at the inverter (Figure 4-b). The PWM 1 and PWM 2 control signals for the BDC are generated by PID control with the value of I_{ref} and the instantaneous operating current of the battery (I_{op}) (Figure 4-c).

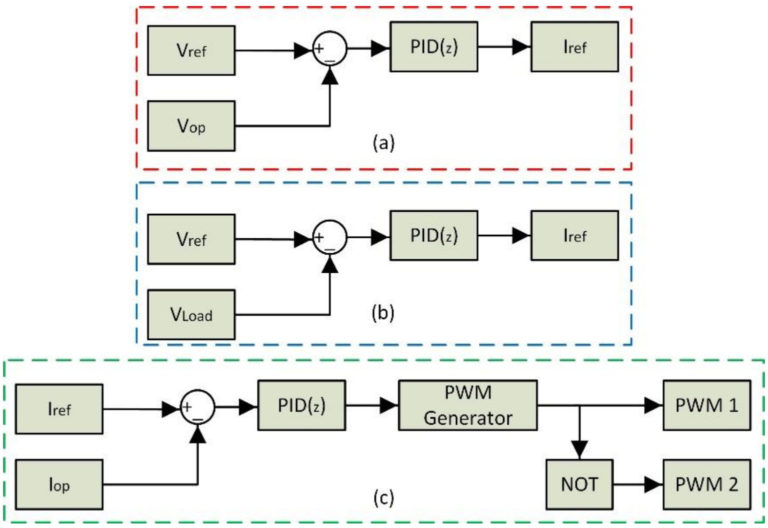

Figure 4. (a) Generation of reference current (I_{ref}) for battery charging (b) Generation of reference current (I_{ref}) for battery discharging (c) Generation of control signal for BDC

2.2. Single-Phase Grid-Connected inverter

When the V2G topology is operated in the designed system, energy is transferred from the EV battery to the grid via a single-phase grid-connected inverter (Figure 5). In the V2G topology, when there is a power demand that exceeds the available power capacity in the MG to which the EV is connected, the EV battery is connected to the grid with a single-phase grid-connected inverter to help meet the power demand.

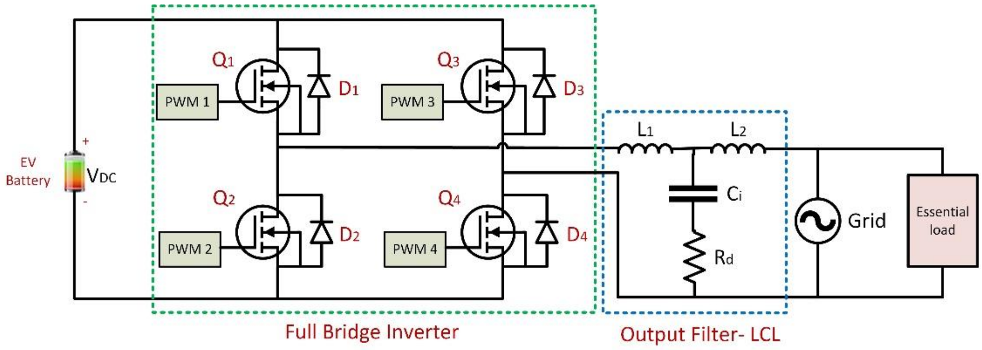

Figure 5. Single-phase grid-connected inverter

The full-bridge inverter is designed for single-phase grid-connected inverters. PWM signals were used for grid connection of the EV battery and energy flow control. The blog diagram of the single-phase grid-connected inverter design is shown in Figure 6. In this blog diagram, PWM control signals are obtained in 5 steps.

- Step 1: Connecting power circuit
- Step 2: Generating α-β voltages and currents
- Step 3: Generating PLL and DQ transformation
- Step 4: Executing current control with PI
- Step 5: Generating PWM signals for power circuit

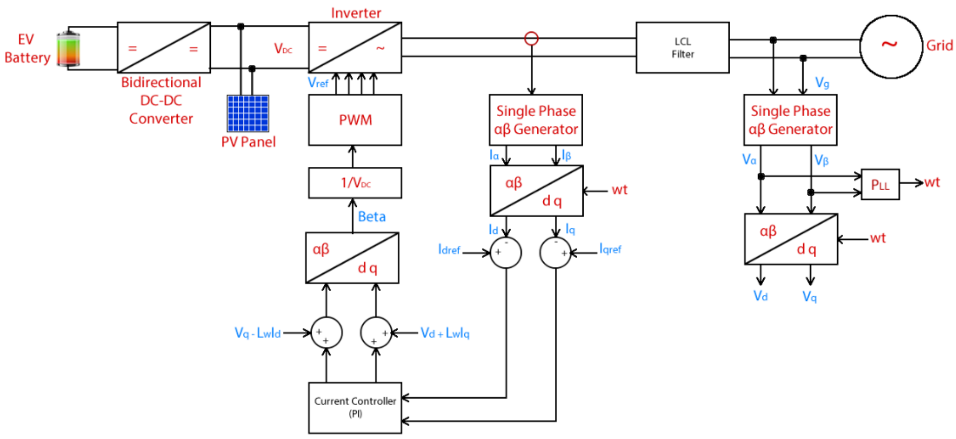

Figure 6. Single-phase grid-connected inverter blog diagram

During the transfer of energy from the EV battery to the grid, harmonics are generated due to the switching elements used in the inverter [24]. The total harmonic distortion (THD) of the fundamental frequency current transferred to the grid must comply with international standards for grid-connected inverters [2]. In order to transfer the current from the EV battery to the grid in accordance with the standards, a filter must be used at the inverter output. The most widely used filter type is the LCL filter, because it is smaller in size and more cost-effective than other filters. However, determining the parameters of the LCL filter is more complex. Therefore, the parameters must be accurately calculated and determined in order to maintain the steady-state state of the system [2].

After determining the values of the variables of the single-phase grid-connected inverter circuit, the values of the LCL filter variables must be calculated. The variables that need to be known in a single-phase grid-connected inverter are as follows:

- V_g : *Grid voltage*
- P_n : *Inverter output power*
- V_{DC} : *DC input voltage (EV battery voltage)*
- f_g : *Grid frequency*
- f_{sw} : *Switching frequency*
- T_{sw} : *Inverter switching time*
- m : *Inverter modulation factor*

The first step in LCL filter design is to select the resonant frequency (f_r) away from the grid frequency (Equation 9).

$$f_r = \frac{1}{2\pi}\sqrt{\frac{L_1+L_2}{L_1L_2C_i}} \tag{9}$$

The performance of the LCL filter is affected by the selected f_r, the value of the capacitor C_i, and the inductance values of the coils L_1 and L_2. Therefore, equation 10 should be used to determine f_r.

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

Reactive power in the grid can cause the capacitor (C_i) to resonate. Therefore, passive or active damping should be added to the capacitor. In this study, passive damping is performed by connecting a damping resistor R_d in series with the capacitor. The value of R_d connected in series with the filter capacitor is calculated as follows.

$$R_d = \frac{1}{3w_rC_i} \tag{11}$$

Filter values are calculated using Base Impedance (Z_b) and Base Capacitance (C_b) values [2,25].

$$Z_b = \frac{V_g^2}{P_n} \tag{12}$$

$$C_b = \frac{1}{2\pi f_g Z_b} \tag{13}$$

In the calculation of the filter capacitance C_i, the power correction factor is chosen as maximum of 5%. Therefore, the calculated C_i value is equal to 5% of the C_b value.

$$C_i = 0.05C_b \tag{14}$$

The maximum amount of ripple in the current at the inverter output ΔI_{Lmax} is calculated as follows:

$$\Delta I_{Lmax} = \frac{2V_{DC}}{3L_1}(1-m)mT_{sw} \tag{15}$$

The highest peak-to-peak current harmonic occurs at m = 0.5. Therefore, ΔI_{Lmax} can also be expressed as follows.

$$\Delta I_{Lmax} = \frac{V_{DC}}{6f_{sw}L_1} \tag{16}$$

For the maximum rated current of the inductor L_1, ΔI_{Lmax} is also expressed as:

$$\Delta I_{Lmax} = 0.1I_{max} \tag{17}$$

$$I_{max} = \frac{P_n\sqrt{2}}{V_p} \tag{18}$$

With these equations, the L_1 value is calculated as shown in equation 19.

$$L_1 = \frac{V_{dc}}{6 f_{sw} \Delta I_{Lmax}} \tag{19}$$

The LCL filter equivalent circuit is analyzed as a current source to calculate the ripple reduction for harmonic frequencies. The LCL filter limits 20% of its own value to reduce the expected 10% current ripple, resulting in a 2% ripple in the output current [26,27]. The relation between the harmonic current of the inverter and the grid and its simplified form is given in Equation 20.

$$\frac{i_g}{i_i} = \frac{1}{\left|1+r\left|1-L_1 C_b w_{sw}^2 x\right|\right|} = k_a \tag{20}$$

The L_2 value is calculated using the constant value of the reduction ratio k_a obtained from equation 20 as follows.

$$L_2 = \frac{\sqrt{\frac{1}{k_a^2}}+1}{C_{if} w_{sw}^2} \tag{21}$$

The ratio of the inductances L_1 and L_2 is defined as the constant r. The equation in this case is given in equation 22.

$$L_2 = r L_1 \tag{22}$$

3. Simulation and Results of The Designed System

The energy flow management designed for the V2G topology consists of four main components: conventional grid, home, EV and PV. The BDC is designed to control the energy flow between PV and EV battery and between EV battery and single-phase grid-connected inverter. In addition, the single-phase grid-connected inverter is designed to transfer energy from the EV battery to the grid. The designed energy flow model was created in MATLAB 2020b/Simulink program. The grid values for the simulation of the model and the component values of the designed system are given in Table 1. The simulations of the designed energy flow model were performed by using these values.

Table 1. The designed system parameters

Symbol	The designed system parameters	Values
V_g	Grid voltage	230 V
V_{Bch}	EV battery charge voltage	330 V
V_{Bdch}	EV battery discharge voltage	322 V
V_{PV}	PV output voltage	530 V
f_g	Grid frequency	50 Hz
f_{sw}	Switching frequency	10 kHz
L	BDC inductor	4 mH
C_i	BDC capacitor	1000 µf
L_1	Inverter side inductor of LCL filter	4.06 mH
L_2	Grid side inductor of LCL silter	4.35 mH
C_i	Capacitor of LCL filter	6.01 µf
Rd	Damping resistor	1 Ω

The simulation of the designed system is performed between time t=0 and t=0.5. The grid feeds a 1kW load from t=0 to t=0.1. Another 2kW load is connected to the grid at t=0.15 and the grid feeds a total of 3kW load. The EV battery is connected to the grid at t=0.2, and 1,8 kW of the 3 kW load is supplied by the grid and 1,2 kW by the EV battery (Figure 7).

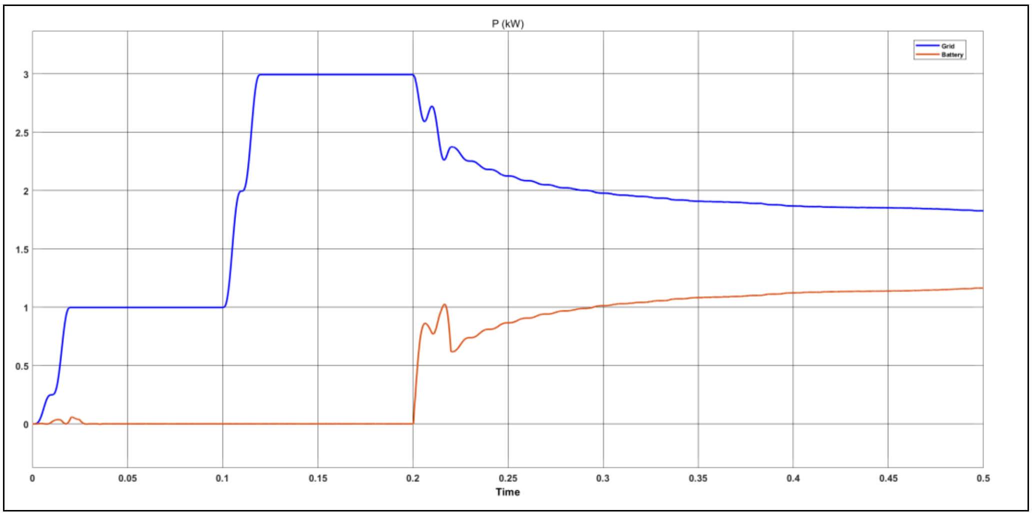

Figure 7. Grid and EV battery power flow chart

Figure 8 shows the current and voltage graphs of the grid. The grid voltage remains constant throughout the simulation. Until t=0.1, the grid current for a 1 kW load is measured as I_{RMS}= 4,3 A. Since the total load is 3kW, the current drawn begins to be measured as I_{RMS}=12,7A at t=0.1. When the EV battery is connected to the grid at time t=0.2, the grid current decreases to I_{RMS} = 10,6 A as the grid starts to consume 1,8 kW of the 3 kW load.

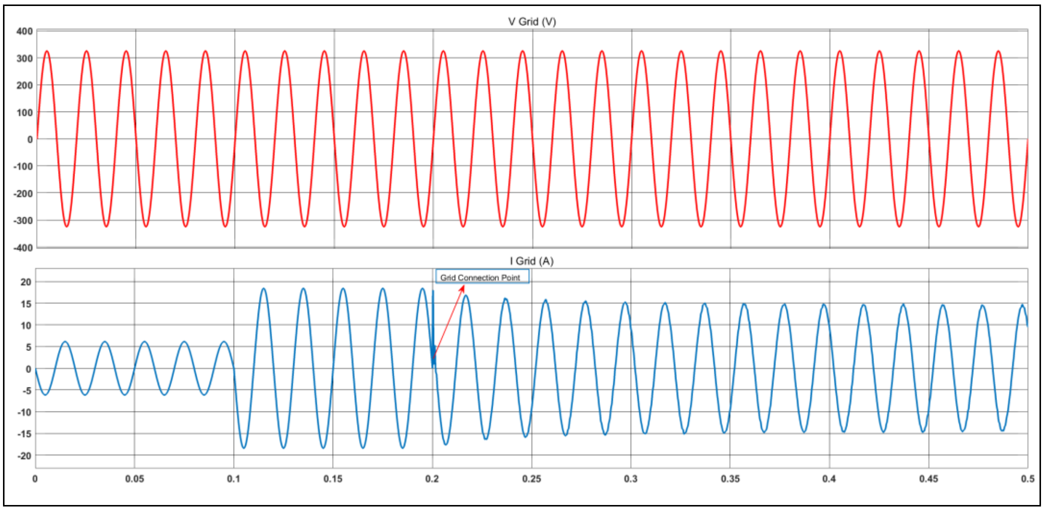

Figure 8. V-I graph of the grid

The graph of the EV battery's current, voltage, state of charge (SOC) and power values is shown in Figure 9. Until the moment t=0.2, the PV panel charges the EV battery in the buck mode of the BDC. The EV battery feeds the grid with a single-phase grid-connected inverter from the moment t=0.2 to t=0.5 in the boost mode of the BDC. Until t=0.2 the SOC of the EV battery increases, after t=0.2 the SOC starts to decrease. The EV battery charges at 330V 40A and discharges at 322V 32A. The current graph shows that the current changes direction between charge and discharge.

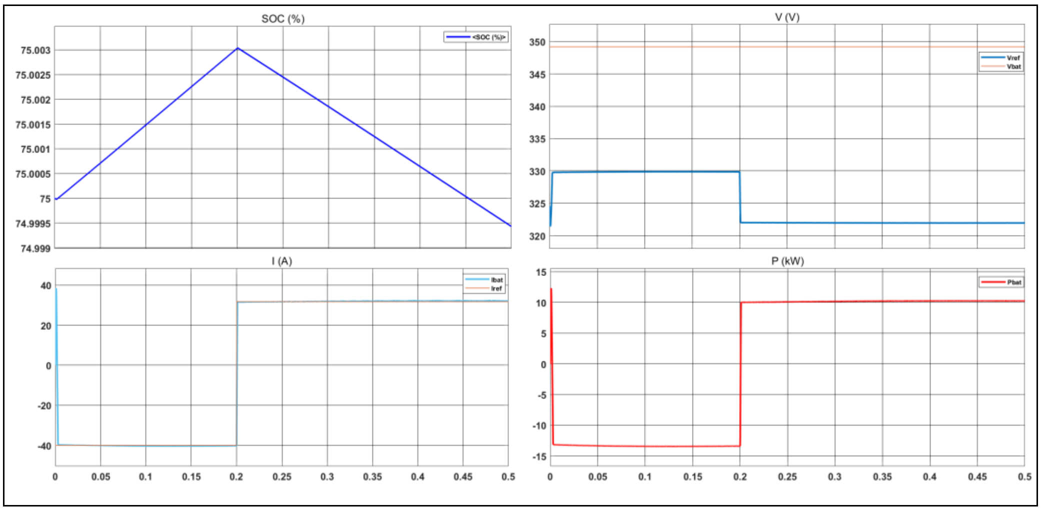

Figure 9. SOC, current, voltage and power graph of EV battery

In order for the PV panel to charge the EV battery from t=0 to t=0.2, I_r was set to 1000A and T=25 °C. While the EV battery is charging, the PV panel provides a voltage of 510 V and a current of 25 A. At t=0.2, the current drawn is 0. Figure 10 shows the current, voltage, power, and I_{diode} graphs of the PV panel.

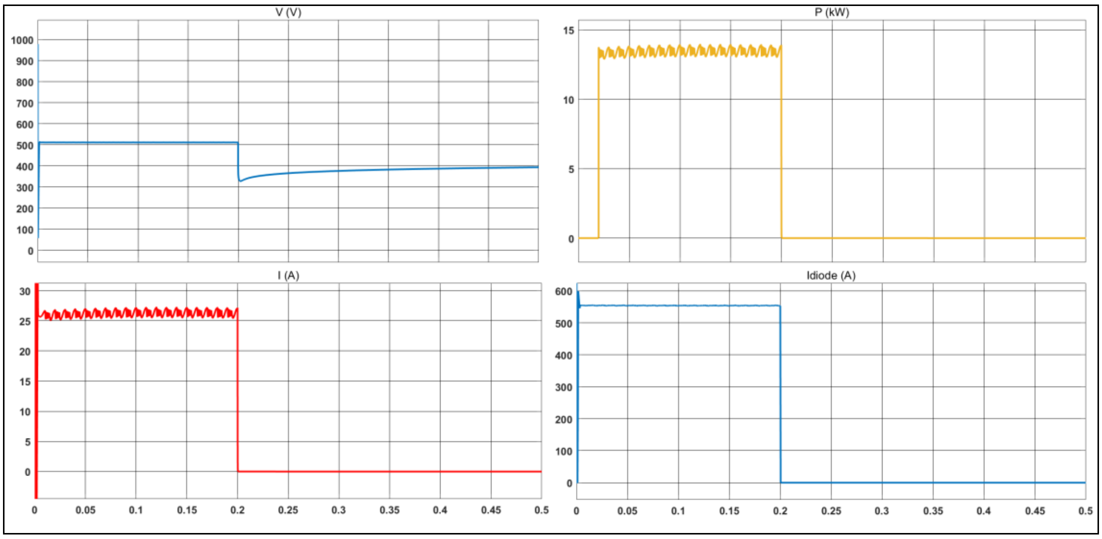

Figure 10. SOC, current, voltage and power graph of EV battery

According to the IEEE-519 harmonic standards, the THD value of the current drawn from the grid should be less than 5%. The THD value of the network was determined to be 1.28% using the FFT analysis (Figure 11).

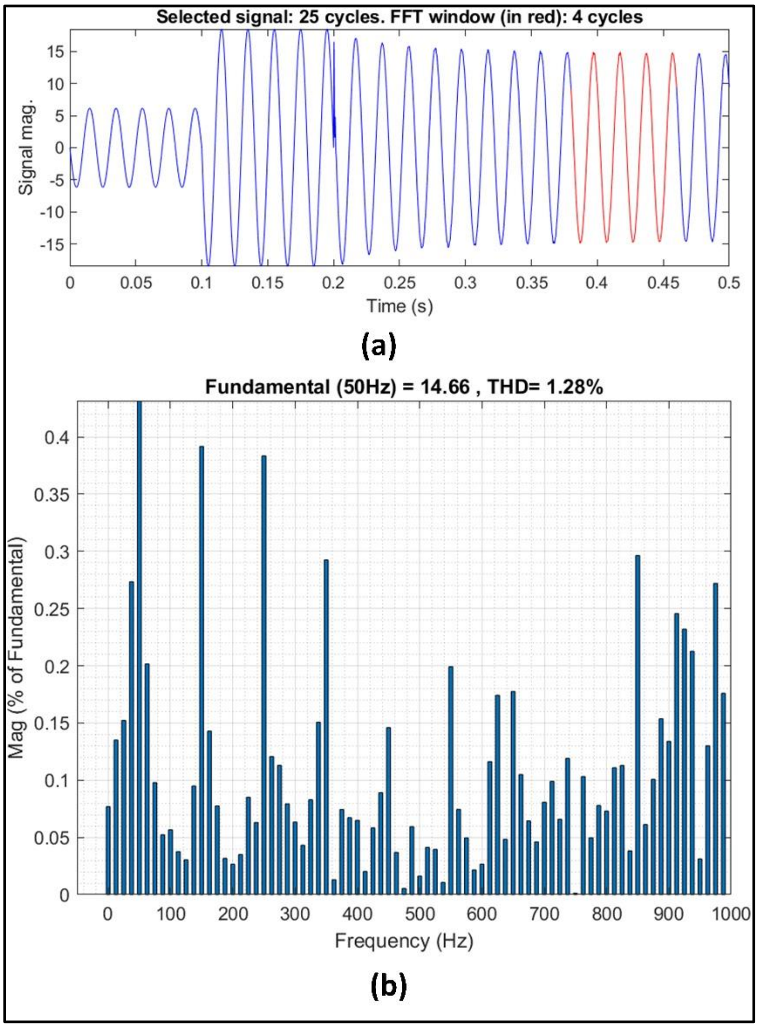

Figure 11. (a) FTT analyze of grid signal (b) THD value of grid

4. Conclusion

The number of EVs is increasing day by day. This increase disrupts the supply and demand balance in existing electricity grids. Therefore, the demand for renewable energy sources is also increasing. The increasing number of EVs is expected to have a negative impact on the power quality of existing conventional grids in the near future. With this rapid increase in EVs, grid integration adds unpredictable large loads to the grid, causing power quality issues such as frequency instability, voltage fluctuations, charging harmonics, and unbalanced loads on the grid. Topologies such as G2V, V2G, V2V, and V2H are being studied to address these negative impacts. As EVs become more widespread, some revisions or changes will be necessary, even if the infrastructure of the countries is sufficient. At this point, minimizing these infrastructure changes, which require very high costs, depends on such management algorithms and the integration of renewable energy sources into charging stations. Therefore, in this study, a feasible model for single-phase energy management in V2G topology is designed. In the designed system, an MG was created for single-phase power flow in V2G topology. This MG includes an EV, a house, and a PV panel. The PV panel charges the EV battery and the EV battery supports the conventional grid. BDC and single-phase grid-connected inverter were designed for this energy flow management. This designed system was simulated and tested for applicability. In the first stage, the EV battery was charged by the PV panel. The buck mode of the BDC was used in this charging process. The EV battery was charged by drawing 13kW of power from the PV panel. The EV battery discharged in the boost mode of the BDC and transferred 10 kW of power to the conventional grid. The EV battery transferred the required power to the conventional grid with a single-phase grid-connected inverter. The filter at the output of the inverter, which is used for harmonics caused by switching elements in the inverters used to connect EVs to the grid, is becoming increasingly important. The LCL filter design was implemented to prevent inverter harmonics from affecting the grid. The THD of the grid was determined to be 1.28% by FFT analysis. The proposed model is found to be efficient with simulation results. In the designed system, the EV battery is charged by the PV panel and the conventional grid is supported by the EV battery. This system proposes a solution to the power quality problems that may arise in the grid as the number of EVs increases in the future.

Acknowledgment

This study (BAP Project Number: FDK-2023-8335) has been supported by Gazi University Scientific Research Projects Unit. We would like to thank Gazi University Scientific Research Projects Unit for their support.

Conflict of Interest Statement

The authors declare that there is no conflict of interest.

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