Müh.Bil.ve Araş.Dergisi,2022;4(1) 45-53

BMBAD BJESR Mühendislik Bilimleri ve Araştırmaları Dergisi Journal of Engineering Sciences and Researches

Modelling and Control of Single-Phase Bidirectional AC/DC Converter Used in Microgrid Energy Systems

Mikroşebeke Enerji Sistemlerinde Kullanılan Tek Fazlı İki Yönlü AC/DC Dönüştürücünün Modellenmesi ve Kontrolü

[1]Evren ISEN

[1]Bandirma Onyedi Eylul University, Faculty of Engineering and Natural Sciences, Department of Electrical Engineering, Bandirma/Balikesir, Turkey

[1]eisen@bandirma.edu.tr

Araştırma Makalesi/Research Article

ARTICLE INFO

Article history

Received : 2 March 2022
Accepted : 25 March 2022

Keywords:

Converter Modelling, Hysteresis Current Control, Inverter, Microgrid, PWM Rectifier

ABSTRACT

In this study, bidirectional single-phase PWM AC/DC converter that is used in microgrid systems at connection point to the grid, is modelled and controlled. PWM signals of the converter is generated with hysteresis current control technique. The mathematical model is developed in Matlab/Simulink. The converter with 5 kW active power capability is examined in rectifier and inverter mode for steady-state and transient response. Two operation modes of the converter is existed by changing power of the DC load and source. The converter transfers the energy from grid to DC bus in rectifier mode while the energy in the DC bus is transferred to grid in inverter mode. The grid current THD% values meet IEEE 1547 and IEEE 519 standards in both modes with 1.52%. The reactive power support of the converter with phase angle control of the grid current is presented. In both modes, reactive power of 500-900 VAr are provided. The obtained results show the availability of the modelling and control of the converter for active and reactive power generating.

MAKALE BİLGİSİ

Makale Tarihleri

Gönderim : 2 Mart 2022
Kabul : 25 Mart 2022

Anahtar Kelimeler:

Dönüştürücü Modelleme, Histerezis Akım Kontrol, İnverter, Mikroşebeke, PWM Doğrultucu

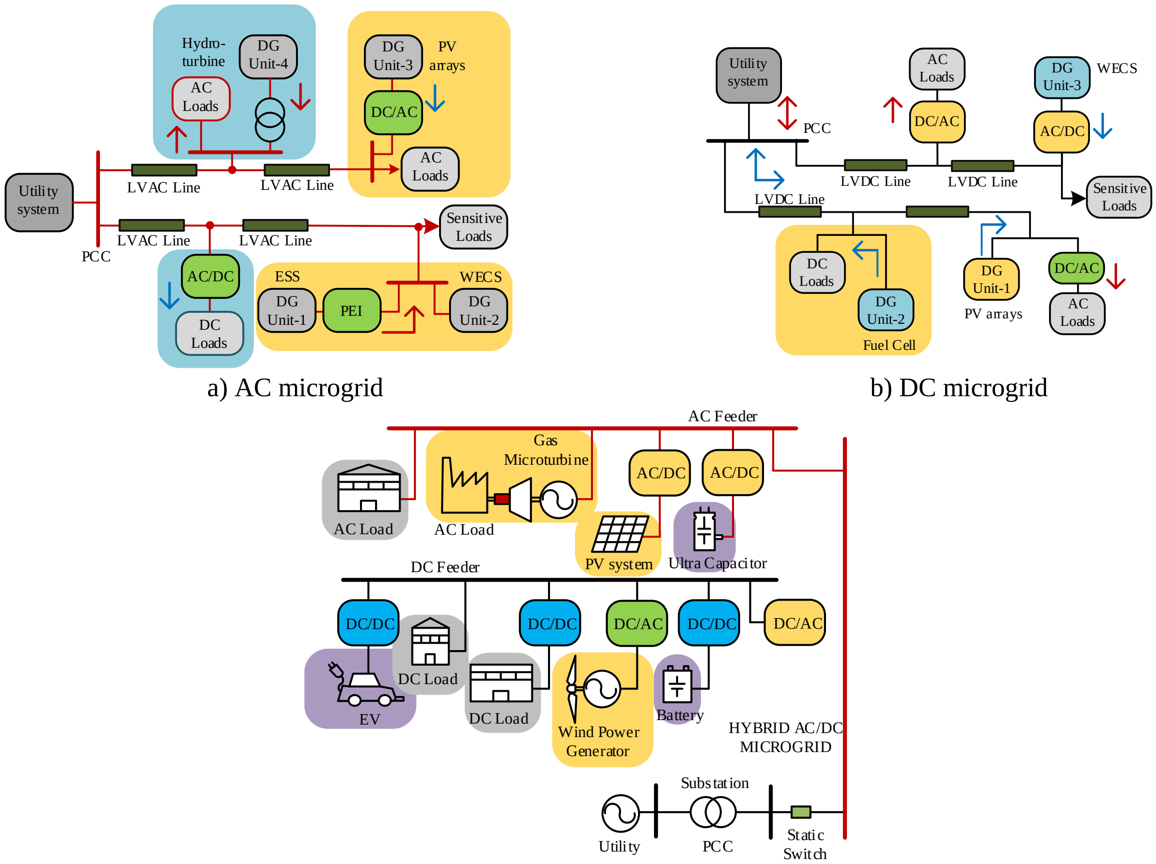
ÖZET

Bu çalışmada mikroşebeke sistemlerde şebeke bağlantı noktasında kullanılan iki yönlü tek fazlı PWM AC/DC dönüştürücünün modellemesi ve kontrolü yapılmıştır. Dönüştürücü kontrolü PWM sinyalleri histerezis akım kontrolü ile elde edilmiştir. Matlab/Simulink ortamında sistemin matematiksel modeli geliştirilmiştir. Dönüştürücü inverter ve doğrultucu modunda 5 kW aktif güç kapasitesinde kararlı hal ve geçici durum cevabı incelenmiştir. Sistemde yeralan DC yük ve kaynağın gücü değiştirilerek dönüştürücünün çalışma modunda değişiklik sağlanmıştır. Dönüştürücü doğrultucu modunda enerjiyi şebekeden DC baraya doğru gönderirken inverter modunda DC baradan şebekeye enerji transferi gerçekleşmiştir. Şebeke akımı %THD değeri incelendiğinde IEEE 1547 ve IEEE 519 standartları her iki çalışma modunda da %1,52 bozulum oranı karşılanmaktadır. Dönüştürücünün doğrultucu ve inverter modunda çalışmasında reaktif güç kontrolü şebeke akımı faz açısı kontrolüyle sağlanmıştır. İki çalışma modunda 500 ile 900 VAr arasında referans değerlerde reaktif güç üretimi ve tüketimi sağlanmıştır. Elde edilen sonuçlar geliştirilen dönüştürücü modelinin ve kontrolünün dönüştürücü aktif ve reaktif güç üretimindeki uygunluğunu göstermektedir.

ORCID ID: [1]0000-0002-3107-9255

1. INTRODUCTION

Due to the depletion of fossil fuels and environmental factors, the use of clean energy is increasing rapidly. With the technological developments in renewable energy systems, there is an increase in distributed power systems and microgrid systems. [1]. Micrograms are energy systems in which different energy sources such as wind turbines, solar panels, hydrogen fuel cells, diesel generators, and batteries are used as storage units, together with the AC grid. Since these systems are installed in areas close to the consumer, they also reduce the losses in energy transmission. They are advantageous systems in terms of efficiency as well as clean energy [2].
In recent years, studies on microgrid systems where renewable energy sources are used and loads can be fed without the need for a grid have become widespread. These systems are called AC microgrid [3], DC microgrid [4] and hybrid microgrid [5], [6] systems as seen in **Figure 1**. These systems include DC and/or AC power supplies. However, since it can be found in both sources in these systems, energy conversion is required. It is possible to convert AC voltage to DC voltage or from DC voltage to AC voltage. For this reason, power electronic converters such as inverter and rectifier circuits are used [7]. If bidirectional conversion is required depending on the operating mode at the same point, a bidirectional PWM AC/DC converter is used at this point. [8]. The converter gives the energy it receives from the grid to the DC bus. However, when the system operating mode changes, it can also give the energy in the DC bus to the grid. This is provided by the bidirectional operation feature. This type of converters are also used in electric vehicles, which are the automobile technology of the future, to transfer energy from the grid to the battery and from the battery to the grid if necessary [9]. It can be used as single-phase and three-phase depending on the power level. Control methods such as bipolar and unipolar PWM [10], hysteresis current control [11], space vector control [12] are used in this converter control. Space vector modulation method is used as an effective method especially in three-phase converter type [13]. The successful operation parameter of this converter in rectifier mode is a smooth DC link voltage regulation, high power factor and low harmonic grid current. It is also low harmonic grid current and high power factor in inverter mode. Basically, while the grid current is in phase with the voltage, that is, high active power transfer is expected, it is also desired to transfer reactive power in special cases [14].



a) AC microgrid b) DC microgrid

c) Hybrid microgrid

Figure 1. Microgrid systems [15, 16].

Microgrid networks can be high-powered as well as being realized in domestic dimensions. The energy produced in these systems, in which wind turbines, solar panels, batteries, and electric vehicles are used, is transmitted to the loads via the AC bus. Thus, there is no need to change the domestic electrical infrastructure [17]. In systems using photovoltaic panels as energy source and lithium-ion batteries as energy storage element, bidirectional

AC/DC converter is used to ensure that the energy transfer in both directions. Depending on the balance of power produced from solar panels and load demand, the flow of energy from the grid to the system or from the system to the grid is controlled [18]. Domestic microgrids can be set up individually as well as locally for more than one household load. A study was carried out on the microgrid modelling and control using photovoltaic panels and batteries for a region with 35 houses in Morocco [19]. Energy and cost savings can be achieved by controlling the individual load of each house in the microgrid designed for regional domestic load, where wind turbines are used as well as photovoltaic panels and batteries [20].
In this study, a single-phase bidirectional AC/DC converter circuit used at the AC grid connection point in microgrid network is simulated. The mathematical model simulation of the converter is carried out in Matlab/Simulink environment. Steady state and transient response are investigated by operating the converter designed with 5 kW power in rectifier and inverter modes. In addition to active power capability, reactive power capability of the converter is presented in both modes for 500-900 VAr reactive power. The mode transition is provided by changing the source and load power. The controller succeeds to transit between operation modes. The converter controlled by hysteresis current control (*HCC*) transfers the energy from the grid to the DC bus in the rectifier mode, while the energy in the DC bus is transferred to the grid in the inverter mode. As the converter is connected to the grid, required synchronization is provided by *dq-PLL* technique. The grid current total harmonic distortion value for both mode meets the standards that are IEEE 1547 and IEEE 519, with 1.52%. With control of the angle of grid current, it is provided to control reactive power.

2. SINGLE-PHASE GRID CONNECTED BIDIRECTIONAL AC/DC CONVERTER

In Figure 2, the circuit diagram of the single-phase bidirectional AC-DC rectifier is given. The converter is connected to the grid via inductance. This inductance is also used in current filtering. It is a filter type that should be used in order for the grid current to have the harmonic content determined in the standards. Although less effective than other filter types, it is preferred in terms of design and control algorithm simplicity. A full bridge converter is included to adjust the conversion and flow of energy. The converter, which contains four switches consisting of a fully controlled semiconductor and a diode connected in reverse parallel to it, can provide bidirectional power flow with PWM control. There is a capacitor at the converter output where the DC bus voltage is provided. The output contains the current source as a simple energy source modelling and the load. The converter power flow direction changes depending on the load's power demand, energy supply power and DC bus voltage value. In this study, the energy balance of the system is changed by changing the source and load current in order to examine the operation in the rectifier and inverter modes, and the mode change of the rectifier is provided.

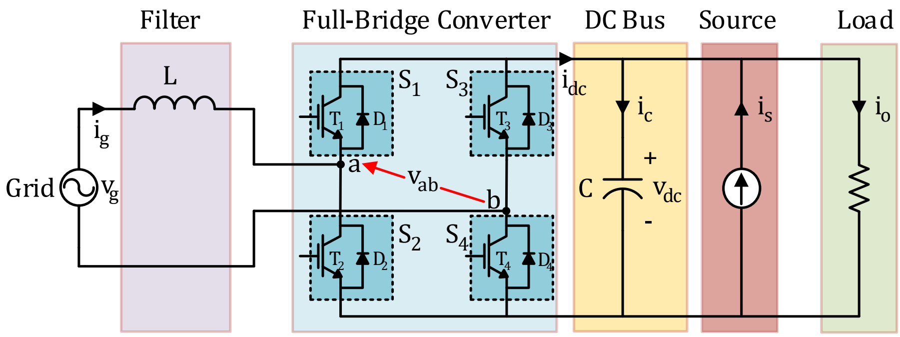


Figure 2. Single-phase grid-connected bidirectional AC-DC rectifier.

Mathematical model of the rectifier is given in (1)-(7). Depending on the voltage law, grid voltage is the sum of inductor voltage and rectifier terminal voltage (v_{ab}) as seen in (1). In the equation, r_L defines the equivalent resistor of the inductor. The differential equation is used to calculate the grid current. Rectifier terminal voltage is equal to voltage difference of terminal points as seen in (2). The voltages of terminals changes depending on the switching state. Equation (3) and (4) gives the voltages of terminal points. In the equations, S_1 and S_3 takes the same value with *S* function that takes value *1* and *-1*. At the output of the rectifier, the flowing current (i_{dc}) depends on grid current. Equation (5) shows the relation between two currents. In the DC side of the rectifier, Equation (6) can be written based on current law. The calculated capacitor current in the equation is used in Equation (7) to calculate capacitor voltage. Using the equations below, a bidirectional rectifier can be derived and simulated.

$$\frac{di_g}{dt} = \frac{v_g - r_L i_g - v_{ab}}{L} \tag{1}$$

$$v_{ab} = v_a - v_b \tag{2}$$

$$v_a = S_1 v_{dc} \tag{3}$$

$$v_b = S_3 v_{dc} \tag{4}$$

$$i_{dc} = S i_g \tag{5}$$

$$i_c = i_{dc} + i_s - i_o \tag{6}$$

$$\frac{dv_c}{dt} = \frac{i_c}{C} \tag{7}$$

The converter operates in rectifier or inverter mode depending on the energy flow. The operating mode of converter changes with the change of grid current flow direction. The modes are examined below. T_x and D_x define transistor and diode of number x, respectively.

2.1. Rectifier Mode

In this mode, the converter works as a PWM rectifier. The energy flows from grid to the DC bus as shown in Figure 3. In the half-period when the grid voltage and current are positive, the T_2 and T_3 switches turn on, and the current drawn from the grid increases. The current passes through the switches and reaches the negative terminal of the DC bus. It causes the decreasing of DC bus voltage. In the same period, when the signals of T_2 and T_3 switches are cut, they turn off, and D_1 and D_4 diodes turn on. In this time interval, the current drawn from the grid decreases, and this current increases the DC bus voltage through the diodes. In the other half-period, when the grid current and voltage are negative, with the T_1 and T_4 switches turning on, the grid current increases in the negative direction, and DC bus discharges. D_2 and D_3 diodes turn on, and the grid current decreases in the negative direction when the T_1 and T_4 switches are off. The DC bus discharges, and thus voltage decreases. The changes in current and voltage depending on the switching signals are given in **Table 1**.

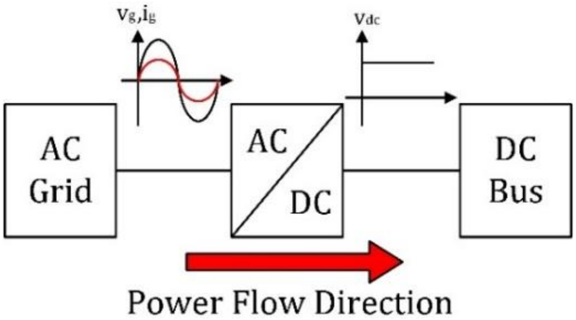


Figure 3. Power flow in rectifier mode.

Table 1. Switching states and electrical quantities.

	Switching		Rectifier and Inverter Mode					Rectifier Mode		Inverter Mode	
Mode	**S_1,S_4**	**S_2,S_3**	**i_{T2},i_{T3}**	**i_{D1},i_{D4}**	**i_{T1},i_{T4}**	**i_{D2},i_{D3}**	**V_{dc}**	**i_g**	**v_g**	**i_g**	**v_g**
1	1	0		↘			↗	↘+	+	↘+	-
2	0	1	↗				↘	+↗	+	+↗	-
3	1	0			↗		↘	-↗	-	-↗	+
4	0	1				↘	↗	↘-	-	↘-	+

2.2. Inverter Mode

The converter runs in inverter mode to convert DC to AC. The energy in DC bus is transferred to the grid by proper switching. The grid current flows in opposite direction according to the rectifier mode. As seen in the Figure 4, the grid current and voltage are in reverse polarity to each other. The change of electrical quantities depending on the switching states are seen Table 1. In the half cycle that voltage is positive and the current is negative, D_2 and D_3 diodes are on when the switching signals are off. The grid current increases in the negative direction, and DC bus voltage decreases. The DC bus voltage increases with D_2 and D_3 diodes are on after T_1 and T_4 switches turn off. The grid current decreases in this time interval. The changes for the other cycle that grid voltage is negative and current is positive, can be seen in Table 1.

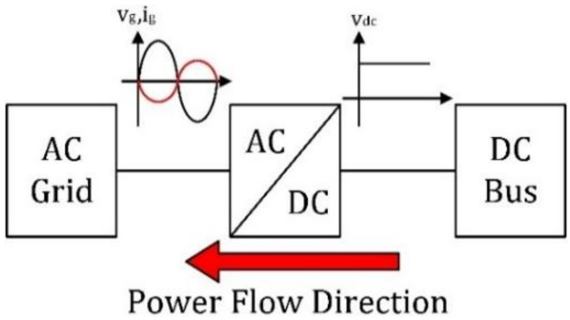
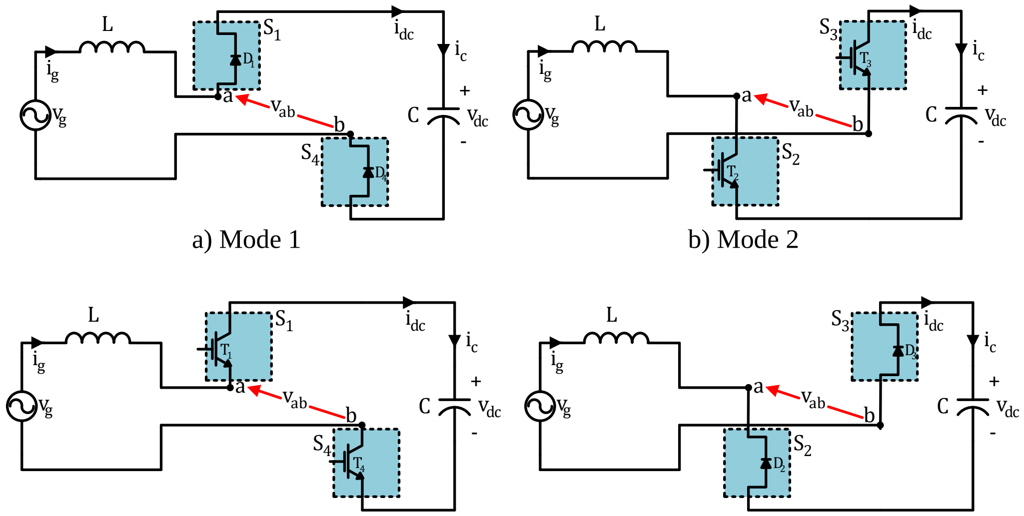


Figure 4. Power flow in inverter mode.

The operation modes of the converter that are explained before are seen in Figure 5. Figure 5a, Figure 5b, Figure 5c and Figure 5d show the topology in mode 1, mode 2, mode 3 and mode 4, respectively. As seen in Table 1, the current of solid-state switches, the grid current and DC bus voltage are affected the same in both inverter and rectifier mode. Therefore, the topologies that are given in Figure 5 is valid for both of them. The difference between rectifier and inverter modes is grid voltage sign. The variation of current and voltage is the same with different grid voltage sign. The same result is observed for the different half cycle of the grid voltage. It means that the same results are obtained in positive half cycle of the grid voltage in rectifier mode with the inverter mode for negative half cycle of the grid voltage.



a) Mode 1 b) Mode 2

c) Mode 3 d) Mode 4

Figure 5. Operation modes of the converter.

3. SIMULATION STUDY

The single-phase bidirectional AC/DC converter is simulated in Matlab/Simulink using mathematical model derived in section 2. The model and control algorithm integrated into Simulink are seen Figure 6. In the model grid voltage is applied with a sinusoidal voltage source. The grid angle (*theta*) is obtained from *PLL*, and it is used in the control algorithm for synchronization. The grid current reference is generated using the DC bus voltage regulation and grid angle. In the control of the rectifier, *HCC* is used to shape the grid current.
In the control of the converter for two modes, the synchronization with the grid is required. Therefore, grid angle must be determined. There are different synchronization methods in the literature. In this study, single phase *PLL* method is used as seen in Figure 6 [21]. *PLL* method is widely used in three-phase systems [22]. Three-phase quantities are converted to two phase quantities in α-β coordinate system. However, there is only a phase in single-phase systems, the other component is obtained with shifting the grid voltage by 90^0. α-β components are seen in Figure 7(a). β- component lags by 90^0 from α-component.
The equations of grid voltage components are given in Equation (8) and Equation (9).

$$v_{g\alpha} = V_{\max}\sin(\omega t) \tag{8}$$

$$v_{g\beta} = V_{\max}\sin(\omega t - 90^0) \tag{9}$$

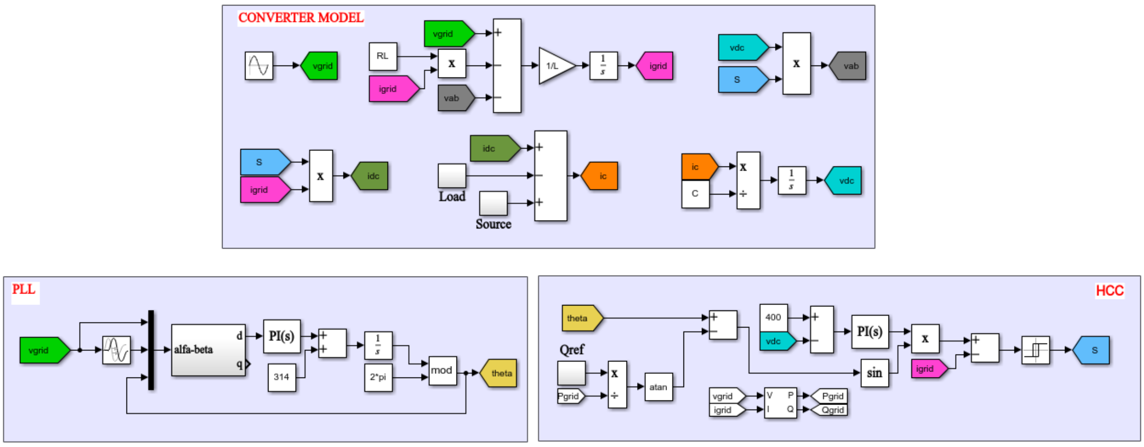
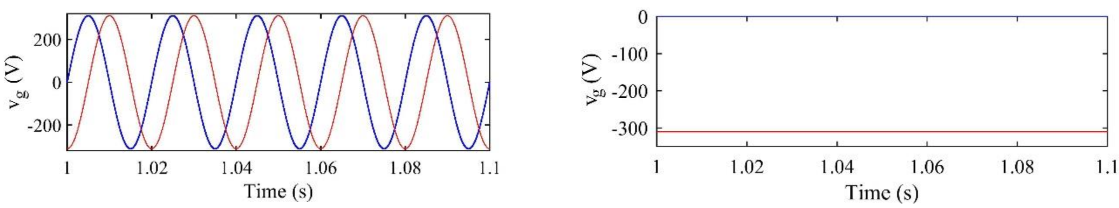


Figure 6. Mathematical model of the bidirectional PWM converter.



a) α-β components (red:β, blue:α) b) d-q components (red:q, blue:d)

Figure 7. Grid voltage components in α-β and d-q coordinate systems.

As the α-β coordinate system components are sinusoidal, they are converted into d-q coordinate system by a transform matrix given in Equation (10). Thus, sinusoidal components are transformed to DC quantities. It makes the calculations easier. The d-q components are seen in Figure 7(b). d-component are used to determine the grid angle. The angle provides grid synchronization. If the grid angle is known, the active and reactive power could be controlled by changing the phase difference between grid voltage and current.

$$\begin{bmatrix} v_{gd} \\ v_{gq} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} v_{g\alpha} \\ v_{g\beta} \end{bmatrix} \tag{10}$$

The circuit parameters that are used in the simulation are given in Table 2. The load and source power is 5 kW, and DC bus voltage is 400 V. In the rectifier mode, the converter regulated the DC bus to 400 V. The grid voltage 220 V, 50 Hz. The filter inductor and capacitor values are 3 mH and 4700 μF, respectively. Figure 8 shows the grid current and switching function. In HCC algorithm, current error is calculated with i_{gref} - i_g equation, and switching function is generated depending on the error value. If the error goes down to negative hysteresis band value (-Δi), it means the grid current reaches to upper limit, and S function takes value 1. In the other state, S function is 0 when the grid current goes down to lower limit. The S function variation depending on the grid current is seen in Figure 8. The Figure 9 shows the grid current for nominal power and grid angle. As seen in Figure 9(a), grid current is synchronized with grid voltage because the grid angle determination algorithm detects the angle well as seen in Figure 9(b).

Table 2. Parameters of bidirectional AC/DC converter and control.

Parameters	**Value**
AC grid voltage (v_g)	220 V
DC bus voltage (v_{dc})	400 V
Maximum Load Power (P_{omax})	5 kW
Maximum Source Power (P_{smax})	5 kW
Capacitance (C)	4700 µF
Filter inductance (L)	3 mH
Hysteresis band (Δi)	0.6 A
K_p, K_i in PLL	2, 1
K_p, K_i in HCC	0.2, 2

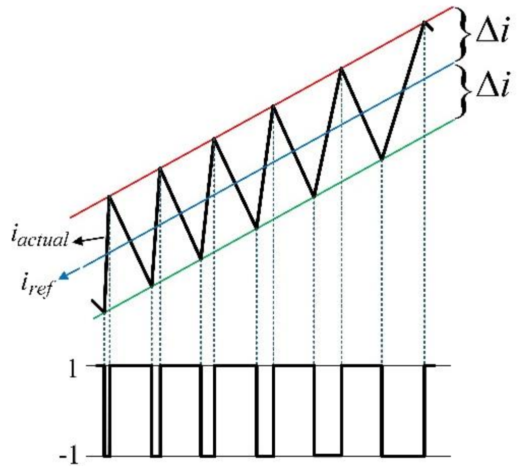
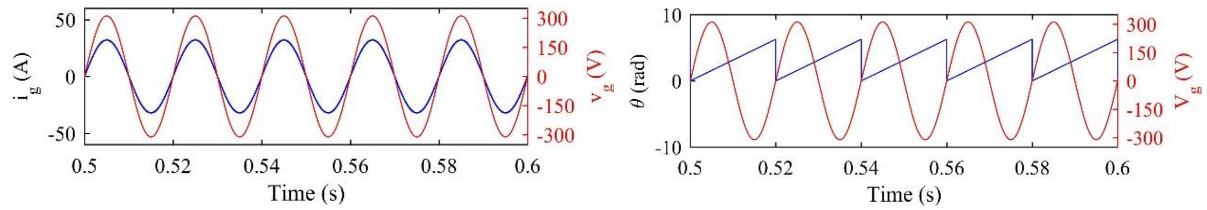


Figure 8. Switching function (*S*) pattern.



a) Grid current and voltage   b) Grid voltage and angle

Figure 9. Steady-state grid synchronization.

The steady-state and dynamic response of the system are seen in Figure 10. While the converter operates at rectifier mode up to 1.2 seconds, the operation mode switches to inverter mode after that time as shown in the Figure 10. The harmonic content of the current for nominal power is THD_I=1.52% in both modes. Figure 11 shows the current waveform in the transition of the modes. As seen in Figure 11, the direction of the grid current changes after 1.2 seconds. The phase difference between the voltage and current becomes 180^0. It means the power flow changes the direction. Before mode change, the power flows from the grid to the system, while it flows from the system to the grid after transition. The reason of the mode transition can be seen from Figure 12. The variations of load and source power and grid power are given in Figure 12(a) and Figure 12(b), respectively. At the transition moment, the load and source power are the same, and the grid power is zero. After that time, the grid power becomes negative because source power is higher than the load power. The excess of the generated power is transferred to the grid. In the steady-state and transient, the DC bus voltage is regulated by the controller. The reference DC bus voltage is set to 400 V_{dc} in the system, and it is regulated as seen in Figure 13.

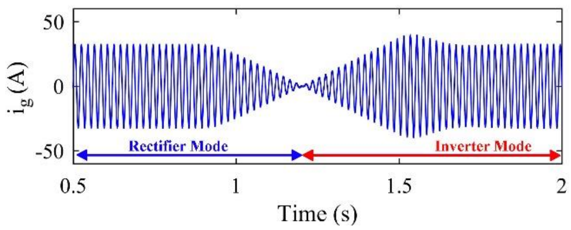


Figure 10. Grid current.

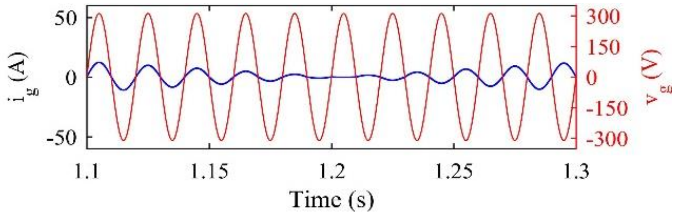
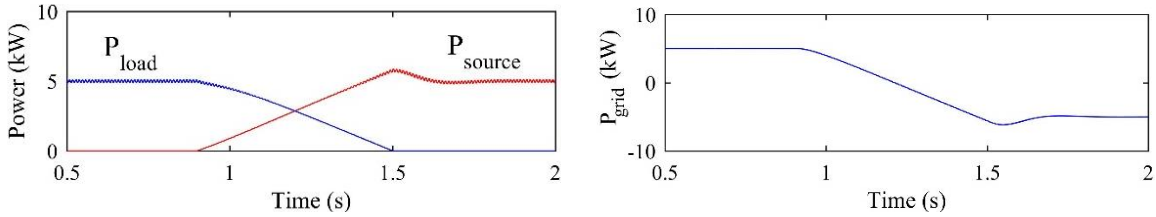


Figure 11. Grid current waveform with grid voltage in rectifier to inverter mode transition.



a) Load and source power b) Grid power

Figure 12. Power variations in the system.

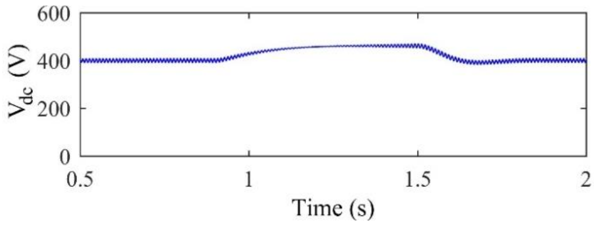
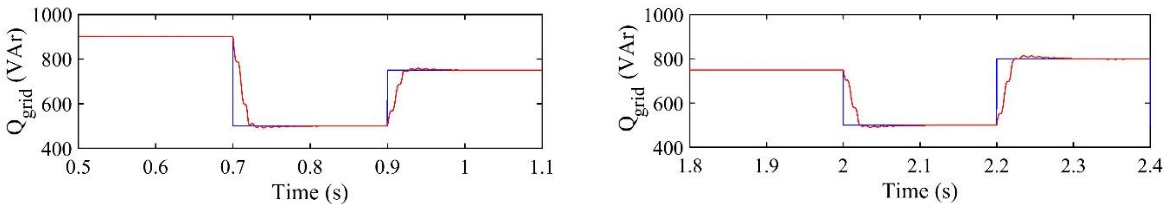


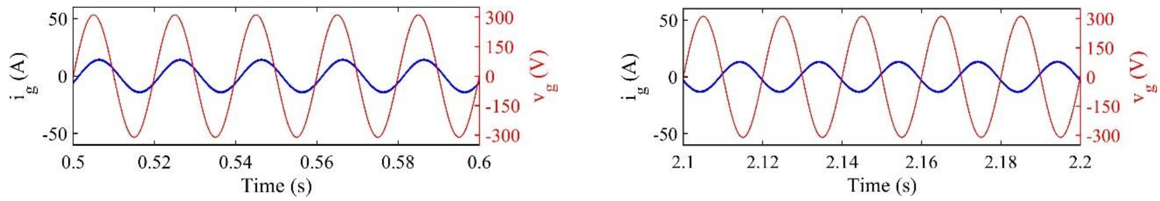
Figure 13. DC bus voltage waveform.

The grid connected systems have a reactive power compensation skill. It is modelled in the simulation to present the feature of reactive power compensation. As seen in Figure 14, different reference reactive power values are applied to the controller. 900, 500 and 750 VAr reactive power variation of grid is seen in Figure 14(a) for rectifier mode. Figure 14(b) shows the reactive power variation of 750, 500 and 800 VAr in inverter mode.



a) Rectifier mode b) Inverter mode

Figure 14. Reactive power variation (Blue: reference value, red: actual value).



a) Rectifier mode b) Inverter mode

Figure 15. Grid current and voltage for reactive power.

4. CONCLUSION

In this study, a 5 kW single-phase bidirectional AC-DC converter is modelled and controlled in Matlab/Simulink. The converter is connected to the grid, and it is operated in rectifier and inverter modes. As the converter is grid connected, the synchronization is required, and the synchronization with the grid is achieved by phase-lock-loop in *d-q* coordinate system. In both modes, the converter is controlled by hysteresis current control technique. In order to examine the operating performance of the converter in two modes, a DC load and a current source representing the renewable energy source are connected to the DC bus. Thus, the power balance of the system is changed, and the converter is enabled to operate in different modes. With the control of the converter, the grid current *THD* value for both operating modes meet the standards with 1.52%. The converter, which works synchronously with the grid, and works with a high power factor in normal operation. As reactive power compensation is required in microgrid systems, reactive power ability of the converter is simulated for 500-900 VAr reactive power. The simulation results shows the ability of reactive power capability of the converter in both modes, successfully.

Statement of Conflict of Interest:

Author has declared no conflict of interest.

Author's Contributions:

The contribution of the authors is equal.

REFERENCES

[1] I. Cetinbas, B. Tamyurek, and M. Demirtas, "Optimal Design of a Microgrid with PV Generation and Energy Storage Unit to Reduce Electricity Cost in Eskisehir Osmangazi University Campus", EMO Bilimsel Dergi, vol. 8, no. 1, pp. 33-38, 2018.

[2] A. S. Aziz, M. F. N. Tajuddin, M. R. Adzman, M. A. M. Ramli and S. Mekhilef, "Energy Management and Optimization of a PV/Diesel/Battery Hybrid Energy System Using a Combined Dispatch Strategy", Sustainability, vol. 11, no. 683, pp. 1-26, 2019.

[3] D. Emara, M. Ezzat, A. Y. Abdelaziz, K. Mahmoud, M. Lehtonen and M.M.F. Darwish, "Novel Control Strategy for Enhancing Microgrid Operation Connected to Photovoltaic Generation and Energy Storage Systems", Electronics, vol. 10, no. 1261, pp. 1-17, 2021.

[4] S. Vasantharaj, V. Indragandhi, V. Subramaniyaswamy, Y. Teekaraman, R. Kuppusamy and S. Nikolovski, "Efficient Control of DC Microgrid with Hybrid PV-Fuel Cell and Energy Storage Systems", Energies, vol. 14, no. 3234, pp. 1-18, 2021.

[5] J. Jiao, R. Meng, Z. Guan, C. Ren, L. Wang and B. Zhang, "Grid-connected Control Strategy for Bidirectional AC-DC Interlinking Converter in AC-DC Hybrid Microgrid", *IEEE* 10th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), pp. 341-345, 2019.

[6] F. Gao, X. Wang, P. Yang, S. Kou and M. Sun, "Research and Simulation of Hybrid AC/DC Microgrid", 4th International Conference on HVDC, pp. 1276-1280, 2020.

[7] X. Wang, J.M. Guerrero, F. Blaabjerg and Z. Chen, "A Review of Power Electronics Based Microgrids", International Journal of Power Electronics, vol. 12, no. 1, pp. 181-192, 2012.

[8] C. Kalavalli, K. ParkaviKathirvelu and R. Balasubramanian, "Single Phase Bidirectional PWM Converter for Microgrid System", International Journal of Engineering and Technology, vol. 5, no. 3, pp. 2436-2441, 2013.

[9] C. K. Gowda, V. G. Khedekar, N. Anandh, L. R. S. Paragond and P. Kulkarni, "Bidirectional on-board EV battery charger with V2H application", 2019 Innovations in Power and Advanced Computing Technologies (i-PACT), pp.1-5, 2019.

[10] V. Vivek and V. A. Manjusha, "Bidirectional AC/DC Converter Using Simplified PWM with Feed-Forward Control", International Journal of Innovative Research in Science, Engineering and Technology, vol. 5, no. 7, pp. 12426-12433, 2016.

[11] E. Isen, "Modeling and Simulation of Hysteresis Current Controlled Single-Phase Grid-Connected Inverter", 17th International Conference on Electrical and Power Engineering, pp. 322-326, 2015.

[12] A. Sangari, R. Umamaheswari, M. G. Umamaheswari and S. Lekshmi, "A novel SOSMC based SVPWM control of Z-source inverter for AC microgrid applications", Microprocessors and Microsystems, vol. 75, pp. 1-13, 2020.

[13] E. Isen and A. F. Bakan, "10 kW grid-connected three-phase inverter system: Control, simulation and experimental results", IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG), pp. 836-840, 2012.

[14] S. Paghdar, U. Sipai, K. Ambasana and P. J. Chauhan, "Active and reactive power control of grid connected distributed generation system", Second International Conference on Electrical, Computer and Communication Technologies (ICECCT), pp. 1-7, 2017.

[15] J. J. Justo, F. Mwasilu, J. Lee and J. W. Jung, "AC-microgrids versus DC-microgrids with distributed energy resources: A review", Renewable and Sustainable Energy Reviews, vol. 24, pp. 387-405, 2013.

[16] A. M. R. Lede, M. G. Molina, M. Martinez and P. E. Mercado, "Microgrid Architectures for Distributed Generation: A Brief Review", IEEE PES Innovative Smart Grid Technologies Conference-Latin America (ISGT Latin America), pp. 1-7, 2017.

[17] E. R. Diaz, E. J. P. Garcia, A. A. Moghaddam, J. C. Vasquez and J. Guerrero, "Real-Time Energy Management System for a Hybrid AC/DC Residential Microgrid", IEEE Second International Conference on DC Microgrids (ICDCM), pp. 256-261, 2017.

[18] M. A Alarcon, R. G. Alarcon, A. H. Gonzalez and A. Ferramosca, "Modeling a residential microgrid for energy management", 2020 Argentine Conference on Automatic Control (AADECA), pp. 1-6, 2020.

[19] K. Tazi, F. Abdi, A. B. Chaka and F. M. Abbou, "Modeling and simulation of a residential microgrid supplied with PV/batteries in connected/disconnected modes-Case of Morocco", Journal of Renewable and Sustainable Energy, vol. 9, no. 025503, pp. 1-15, 2017.

[20] M. M. U. Rashid, M. A. Alotaibi, A. H. Chowdhury, M. Rahman, M. S. Alam, M. A. Hossain and M. A. Abido, "Home Energy Management for Community Microgrids Using Optimal Power Sharing Algorithm", Energies, vol. 14, no. 1060, pp. 1-21, 2021.

[21] C. Picardi, D. Sgro and G. Gioffre, "A simple and low-cost PLL structure for single-phase grid-connected inverters", SPEEDAM 2010, pp. 358-362, 2010.

[22] Z. Ali, N. Christofides, L. Hadjidemetriou, E. Kyriakides, Y. Yang and F. Blaabjerg, "Three-phase phase-locked loop synchronization algorithms for grid-connected renewable energy systems: A review", Renewable and Sustainable Energy Reviews, vol. 90, pp. 434-452, 2018.