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# Tek fazlı şebekeye bağlı evirici tasarımı ve kontrolü

# *Design and control of a single-phase grid-connected inverter*

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# Tek Fazlı Şebekeye Bağlı Evirici Tasarımı ve Kontrolü

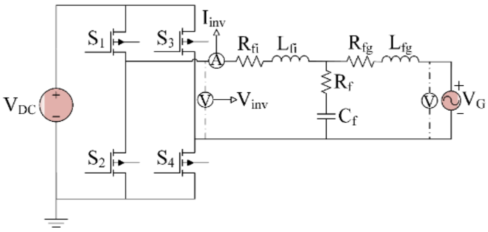
## Design and Control of A Single-Phase Grid-Connected Inverter

### *Highlights*

- *Döngü-Döngü ortalama (DDO) modeli, temel tek fazlı şebekeye bağlı eviricide tartışılmıştır./ The cycle-by-cycle average (CCA) model is discussed in a basic grid-connected inverter with a single-phase structure.*
- *DQ eksende akım kontrolü önerilmiş ve onun performans değerlendirmesi farklı akım referansları altında sunulmuştur./ A current controller in dq-frame is proposed and its performance evaluation is presented under different current references.*

### *Graphical Abstract*

*Bu makalede, LCL filtreli tek fazlı şebekeye bağlı evirici kapsamlı şekilde incelenmiştir./ In this paper, a single-phase grid connected inverter is evaluated in detail.*




**Şekil.** LCL filtreli tek fazlı şebekeye bağlı evirici **/ Figure.** A single-phase grid-connected inverter with LCL filter

### *Aim*

*Çalışmanın amacı tek fazlı şebekeye bağlı eviriciyi tasarım ve kontrol açısından kapsamlı şekilde incelemektir./ The aim of the study is to examine the single-phase grid-connected inverter comprehensively in terms of design and control.*

### *Design & Methodology*

*Tek fazlı şebekeye bağlı evirici için dq akım kontrolcüsü tasarlanmıştır. / A dq current controller is designed for a single-phase grid-connected inverter.*

### *Originality*

*Literatürdeki benzer çalışmalarla karşılaştırıldığında, tek fazlı temel bir şebeke bağlantılı eviricinin DDO modelinden detaylı olarak bahsedilmiştir./ Compared with similar studies in the literature, The CCA model of a basic grid-connected inverter with a single-phase structure is mentioned in detail.*

### *Findings*

*Önerilen akım kontrolörü, varyasyonlara karşı oldukça hassastır. DDO modeli, devrenin kolayca gerçekleştirilmesini sağlar. / The proposed current controller is highly sensitive to the variations. The CCA model provides easy to realize the circuitry.*

### *Conclusion*

*Bu makalede, temel şebeke bağlantılı evirici yapısını tasarlamak için DDO modeli sunulmaktadır. Önerilen akım kontrolcüsü varyasyonlar altında iyi bir performans göstermektedir. Son olarak, bu tür evirici topolojisi, gelecekteki güç sisteminde önemli bir rol oynayacaktır./ In this paper, the CCA model is presented to design the basic grid-connected inverter structure. The proposed current controller shows good performance during the variations. Finally, this type of inverter topology will play a crucial role in the future power system.*

### *Declaration of Ethical Standards*

*Bu makalenin yazar(lar)ı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler. / The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.*

# Tek Fazlı Şebekeye Bağlı Evirici Tasarımı ve Kontrolü

***Araştırma Makalesi / Research Article***

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**ÖZ**

Enerji talebi son on yılda artmaktadır. Yenilenebilir enerji kaynaklarının entegrasyonu ile şebekeye bağlı eviciriler bir güç sisteminde önemli bir rol oynamaktadır. Bu makalenin temel amacı, tek fazlı şebeke bağlantılı evirici yapısını detaylı olarak tartışmaktır. Şebekeye bağlı temel bir evirici yapısının tasarımı ve çalışma prensibi, döngü-döngü ortalama (CCA) modeli ile birlikte sunulmaktadır. Mevcut harmonikleri azaltmak için LCL filtre tasarımı da tanıtıldı. Birlik güç faktörü çalışmasını elde etmek için, şebekeye bağlı eviriciler için kapalı çevrim kontrolü gereklidir. Bu nedenle MATLAB/Simulink ortamından yararlanılarak dq eksen'de bir akım kontrolörü gerçekleştirilmiştir. Sonuçlar, önerilen akım kontrolcünün varyasyonlar sırasında iyi performans gösterdiğini bildirmektedir. Bu çalışmanın şebeke bağlantılı evirici tasarımcılarının dikkatini çekmesi ve onlara referans olması beklenmektedir.

**Anahtar Kelimeler: Enerji, şebeke bağlantılı inverter, akım kontrolü, simülasyon.**

# Design and Control of A Single-Phase Grid-Connected Inverter

**ABSTRACT**

The energy demand has been increasing over the last decade. With the integration of renewable energy sources, grid-connected inverters play a key role in a power system. The main objective of the paper is to discuss a grid-connected inverter with single-phase structure in particular. The design and working principle of a basic grid-connected inverter are presented together with the cycle-by-cycle average (CCA) model. The LCL filter design is also introduced to decrease the current harmonics. To attain unity power factor operation, the closed loop control is essential for the grid-connected inverters. For this reason, a current controller in dq-frame is performed by utilizing MATLAB/Simulink environment. The results indicate that the suggested current controller presents good performance during the variations. This study is anticipated to draw the attention of grid-connected inverter designers and serve as a reference for them.

**Keywords: Energy, grid-connected inverter, current control, simulation.**

## 1. INTRODUCTION

Along with the global energy crisis and global warming, the significance of renewable energy will flourish gradually. Countries all over the world take measures to reduce carbon emissions and regulate energy demand. The power electronic components and power converter structures play a crucial role under these endeavors. The power converters are needed where the current, voltage, and frequency of electrical power have to be changed regularly. The inverter is a power electronic circuitry that converts DC power to AC power and is preferred in many application areas, such as solar, microgrid, HVDC power transmission systems, uninterruptible power supplies (UPS), and so on [1-4].

Among the inverter topologies, the single-phase inverter becomes prominent in many application areas in recent times. Specifically, solar applications stand out in accordance with photovoltaic (PV) power generation. There are many surveys in the literature regarding single-phase grid-connected solar inverter structures. Jana et al., reviewed inverter topologies for solar PV systems [5]. The advantages, disadvantages, and main attributes of grid-connected inverter structures are presented in [6]. An analytical approach is also examined in this of type inverter structure to provide the stability of the system [7]. Modeling, analysis, and design studies of grid-connected inverter structures are also investigated in PV integrated applications [8-10]. A grid-connected inverter structure is also evaluated in microgrid applications [11]. A simplified current controller in dq-frame is suggested for PV inverter applications [12]. Herein, an orthogonal signal does not need to be produced, and hence dynamic performance of the system is increased.

In this paper, the fundamental principles of a grid-connected inverter with a single-phase structure are presented, especially the cycle-by-cycle average model highlighted in the design procedure of the basic grid-connected inverter structure. Current control in dq-frame is suggested for this type of inverter structure. The behavior of the proposed current controller is also tested under different current references.

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Following the introductory section, this paper is organized as follows. Section 2 presents the working principle of a grid-connected inverter with a single-phase structure. Section 3 includes one of the design methods of the LCL filter. Section 4 highlights the proposed current control structure. Section 5 presents the simulation model of the suggested system. Finally, a conclusion and discussion are drawn in Section 6.

## 2. DESIGN AND WORKING PRINCIPLE

The basic scheme of a grid-connected inverter with a single-phase structure is depicted in Figure 1. Herein, a full-bridge inverter topology is typically used in grid-connected applications. Considering switching components, IGBT and Mosfet are generally used in grid-connected applications.

The switching is prominent for this type of inverter structure to reduce the harmonics. The unipolar pulse width modulation (UPWM) is typically used as depicted in Figure 2. According to UPWM modulation, two sinusoidal reference waves are used with the same frequency and amplitude but with a complementary phase difference. The obtained reference waves are then used with a triangular wave to obtain PWM signals. The obtained PWM is applied to the upper switches of the inverter while the complementary ones are applied to the lower switches in a sequence. It is something to consider that both switches on the single leg of the inverter should not be ON position at the same time for the UPWM modulation method otherwise a short circuit path occurs across the DC source that can be damaged to switches.

Considering UPWM modulation for this type of inverter, the output voltage changes between VDC and zero in a positive half cycle. Conversely, the output voltage varies between -VDC and zero in a negative half cycle. The unipolar switching method has advantages, such as reduced stress across the switches, filter size, filter cost, and decreased load while the control complexity forms the drawback side of this modulation method [13]. The single-phase grid-connected inverter can be designed using CCA model as depicted in Figure 3.

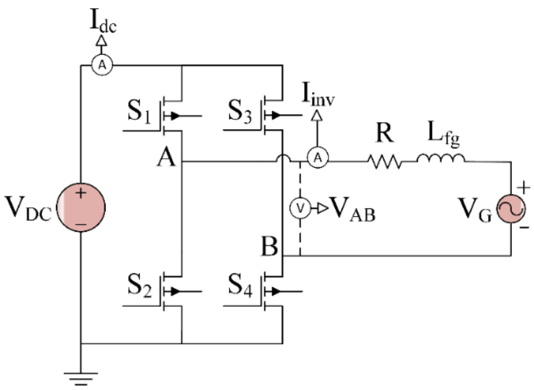


**Figure 1.** Basic scheme of a grid-connected inverter with single-phase structure

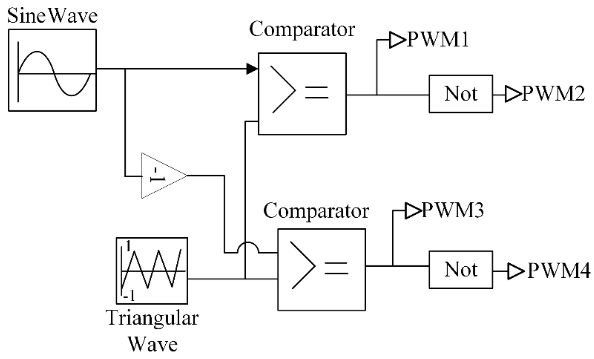


**Figure 2.** The unipolar switching in open loop control

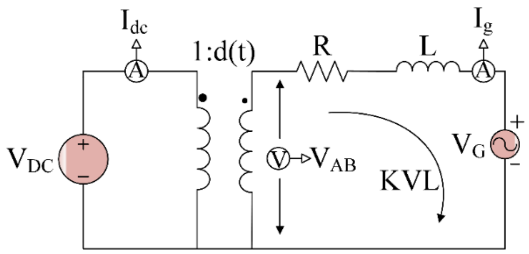


**Figure 3.** The CCA model of a grid-connected inverter with single-phase structure

Herein, the switching components are modeled as an ideal transformer. Using Kirchhoff voltage law (KVL) in the CCA model, the related parameters are determined as follows.

The active power is determined by using grid parameters with a phase difference as follows:

$$P = \frac{V_G * I_g}{2}\cos(\Theta) \tag{1}$$

Using the active power formula, the average grid current is calculated as below.

$$I_g = \frac{2*P}{V_G * \cos(\Theta)} \tag{2}$$

The resistive voltage drop is determined as below.

$$V_R = R \text{ x } I_g \tag{3}$$

Inductive voltage drop is determined as shown below.

$$V_L = jwL \text{ x } I_g \tag{4}$$

The average value of inverter output voltage is calculated as below.

$$\overline{V_{AB}}(t) = V_G + V_L + V_R \tag{5}$$

The duty cycle parameter is determined by,

$$d(t) = \frac{V_{AB}}{V_{DC}} \tag{6}$$

The average dc link current is calculated by,

$$\overline{I_{dc}}(t) = d(t) \text{ x } \overline{I_g}(t) \tag{7}$$

## 3. DESIGN PROCEDURE OF LCL FILTER

The design of filter structure is more important to decrease the high frequency harmonics and undesired ripples for converter structures.

Filter structures are typically formed with passive inductive and capacitive components, such as L, LC and LCL filter. The L filter has the simpliest structure, whereas the increased cost and volume are the drawback side [14]. The basic scheme of a LCL filter is depicted in Figure 4. It consists of passive inductive and capacitive components with their series resistance. The LCL filter has lower current harmonics as compared to basic filter structures, and hence better power quality is achieved in grid-connected applications [15]. However, the complicated structure of the LCL filter is the drawback side.

Parallel resistance and series inductance of the LCL filter are not typically consider to have minimum influence in the frequency span [16].

The inverter-side inductance is aimed to limit the current ripple originating from the inverter. The maximum current ripple and inverter-side inductance are calculated based on output-side voltage and current waveforms of the inverter as depicted in Figure 5. The average value of output voltage is regarded as constant in case of higher switching frequency than the fundamental frequency.

The current value that is peak-to-peak using unipolar PWM could be determined as:

$$\Delta I_{pp} = 2\Delta I_{max} = \frac{(V_{DC}-V_{AV})}{L} * \frac{T_{sw}}{2} * d \quad (8)$$

Assuming the fundamental component of the inverter-side filter is zero, the duty cycle parameter and the average of the output voltage during the period of 0<wt<π can be deduced as:

$$V_{AV} = d * V_{DC} \quad (9)$$

$$d = m_a * \sin wt \quad (10)$$

Using Equations (9) and (10), the peak-to-peak AC current during a period of 0<wt<π can be determined as:

$$\Delta I_{pp} = \frac{V_{DC}*T_{sw}}{2L} * (1 - m_a * \sin wt) * m_a * \sin wt \quad (11)$$

Depending on the magnitude distribution of the inverter using the modulation index term, the maximum current ripple formula is determined as [17]:

$$\Delta I_{max} = \frac{V_{DC}*T_{sw}}{8*L} \quad (12)$$

Thus, the modulation index term does not influence the maximum current ripple and the inverter-side inductance can be determined as:

$$L_{fi} = \frac{V_{DC}*T_{sw}}{8*\Delta I_{max}} \quad (13)$$

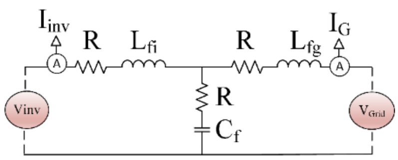


**Figure 4.** The LCL filter structure

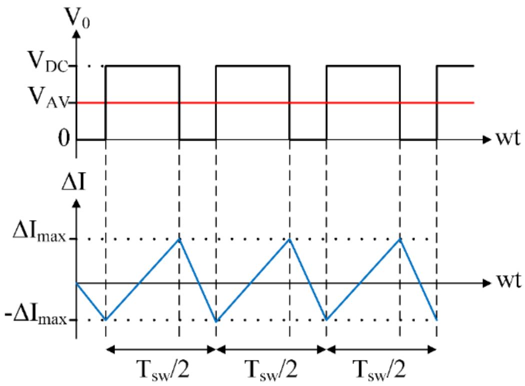


**Figure 5.** The inverter output side voltage and current waveforms

The design procedure for the filter capacitor is related to reactive power absorbing from the grid at nominal conditions. The reactive power is limited to 5% of rated power [18].

$$Q = P * 0.05 = \frac{V^2}{1/(2*pi*f*C)} \quad (14)$$

Hence, the filter capacitor is calculated as:

$$C = \frac{0.05*P}{V^2*2*pi*f} \quad (15)$$

The sum of inverter-side and grid-side inductance value is determined depending on the voltage drop across the load and is selected between the 5 % and 20 % of the rated line-to-neutral grid voltage [14]. In this study, the voltage drop is restricted to 5 % of the nominal voltage.

$$V_{Lfi+Lfg} = I * X_{Lfi+Lfg} = I * 2 * pi * f * (Lfi + Lfg) \quad (16)$$

$$L_{fi} + L_{fg} = \frac{5\% \text{ of } V}{\left(\frac{P}{V}\right)*2*pi*f} \quad (17)$$

$$L_{fg} = \frac{0.025*V^2}{P*pi*f} - L_{fi} \quad (18)$$

## 4. CURRENT CONTROL STRUCTURE

A dq-PLL method is represented in Figure 6. Herein, the park transformation is used to convert the time-varying equations into time-invariant equations. Hence, direct and quadrature components are created via this transformation. The PI controller is used as a loop filter. The integrator side behaves like a voltage-controlled oscillator. The main aim of the dq-PLL is to generate two signals with the same frequency and magnitude.

A grid-tie inverter having a single-phase structure with its current controller is depicted in Figure 7. Direct quadrature (DQ) synchronous reference frame is preferred in the proposed current controller structure due to its superior performance. It drives on dc quantities and provides zero steady-state error. Besides, this transformation-based controller is highly compatible with this type of inverter structure.

The alpha and beta signals are generated utilizing the inverter current and that of the grid voltage parameter.

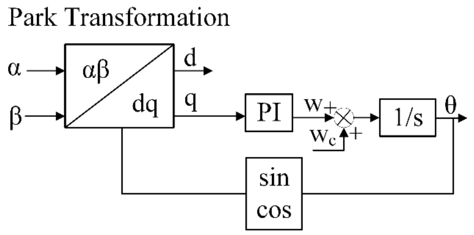


**Figure 6.** Block diagram of a dq-PLL method

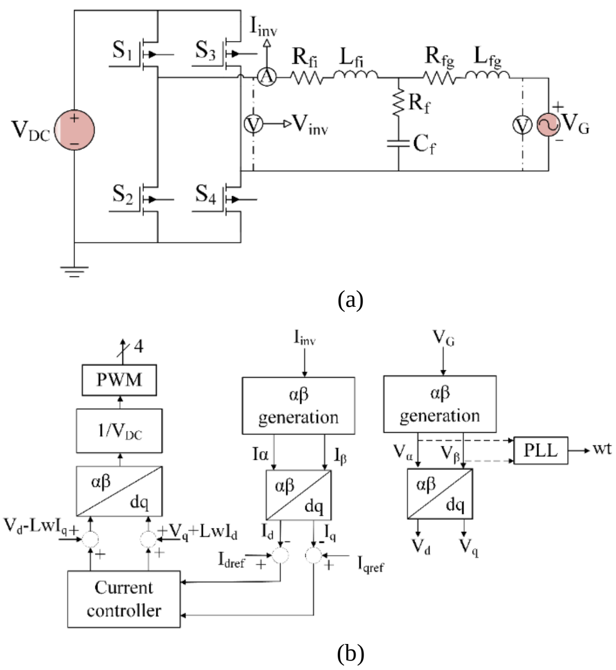


**Figure 7.** A grid-connected inverter with single-phase structure: (a) power subsystem, (b) control subsystem

There is a 90° phase shift between the alpha and beta signals. The principle aim of the current controller is to set the desired values of id and iq current components. Due to the current controller, a power factor of one is aimed among the voltage and current of the grid, and hence reactive power component is highly eliminated.

## 5. SIMULATION WORK

Closed-loop control of a grid-connected inverter with a single-phase structure is evaluated in the section. The simulation work aims to discuss the performance evaluation of the proposed current controller in the dq-frame. The proposed current controller is implemented to the inverter using Matlab/Simulink software. The specifications of the designed inverter are given in Table 1. The series resistance of the inductances and capacitances is 0.001 ohm. As mentioned before, there is a 90° phase shift between the alpha and beta signals demonstrated in Figure 8. The output voltage of the inverter is depicted in Figure 9. Herein, Figure 9 (a) introduces the measured inverter output voltage having a unipolar switching waveform and Figure 9(b) represents the CCA value of the waveform. Hence, higher harmonics have been eliminated by using the CCA method.

The id current component presents active power whereas the iq current component stands for reactive power. First, the reference id current is set to 6 A, and inverter output current is achieved at the desired current value as shown in Figure 10. Herein, the reference iq current is set 0 A, and hence the in-phase operation is achieved for the grid parameters as depicted in Figure 11. When the reference id current changes from 6 A to 2 A at around 0.25s, the current controller gives a good response to the changes as depicted in Figure 12. Furthermore, the power factor of one is achieved during the variation of id current as demonstrated in Figure 13.

The iq current as reference is arranged to 6 A and the reference id current is set to 0 A, the reactive power is created and injected into the grid as opposed to the active power in this operation mode as shown in Figure 14. Moreover, the current leads the voltage. Then, the iq current as reference is arranged to -6 A and the reference id current is set to 0 A, the reactive power is created and absorbed from the grid as depicted in Figure 15. Furthermore, the grid current lags the grid voltage in this operating mode.

**Table 1.** Grid-connected inverter specifications

| Parameter | Definition | Value |
|---|---|---|
| $V_{DC}$ | DC link voltage | 400 V |
| $V_G$ | Grid voltage | 220 $V_{rms}$, 50Hz |
| P | Active power | 1 kW |
| $f_{sw}$ | Switching frequency | 40 kHz |
| $L_{fi}$ | Filter inductance for inverter-side | 1.94 mH |
| $L_{fg}$ | Filter inductance for grid-side | 5.76 mH |
| $C_f$ | Filter capacitance | 3.29 uH |

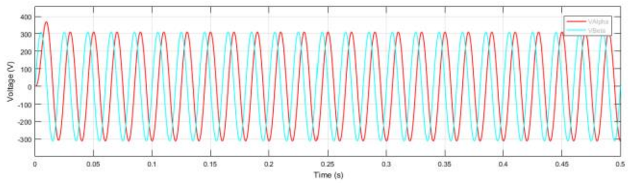


**Figure 8.** Generated alpha and beta signals

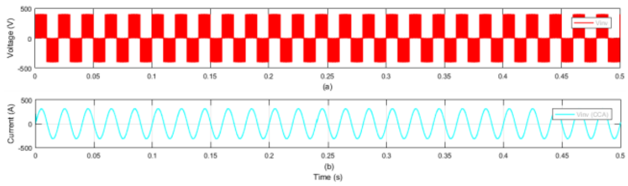


**Figure 9.** Inverter output voltage waveform: (a) measured value, (b) CCA value

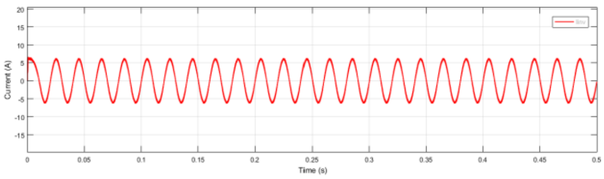

**Figure 10.** Inverter output current waveform

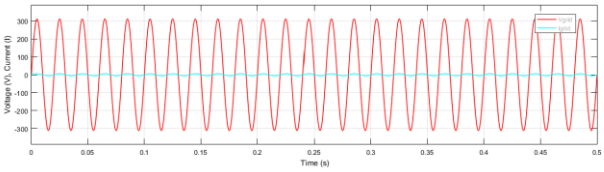

**Figure 11.** Grid current and voltage waveforms in power factor of one

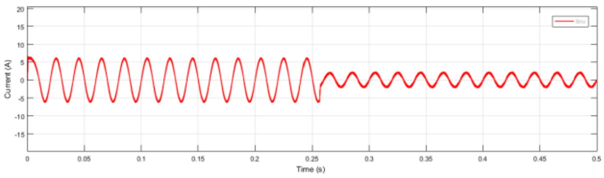

**Figure 12.** Inverter output current when the current reference id changes from 6A to 2A

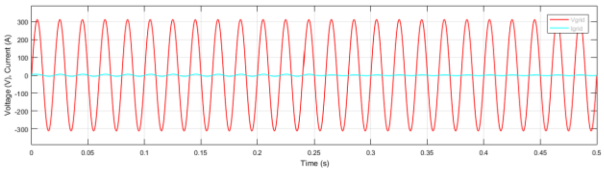

**Figure 13.** Grid current and voltage waveforms when the current reference id varies from 6A to 2A

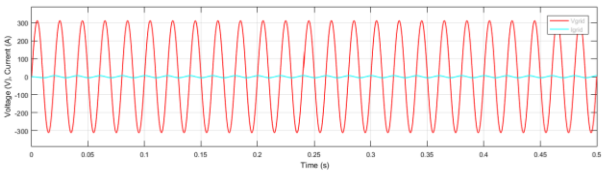

**Figure 14.** Grid current and voltage waveforms when the current reference iq is set to 6A

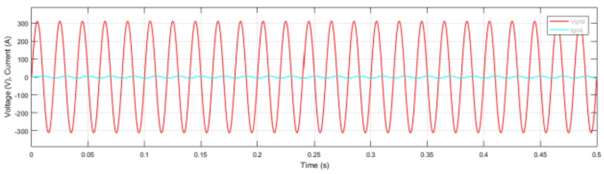

**Figure 15.** Grid current and voltage waveforms when the current reference iq is set to -6A

## 6. CONCLUSION AND DISCUSSION

The single-phase grid-connected inverter topology has drawn attention day by day, especially in renewable energy-based applications. In this paper, this promising converter topology is thoroughly examined, especially highlighting the cycle-by-cycle average model to design process and the behavior of the proposed current controller under different reference current variations. When the current reference is changed, the system gives a good response to the variations. The current reference for the direct axis component is first changed from 6 A to 2 A and the quadrature axis current reference is arranged to zero. For this condition, the voltage and current of the grid are in-phase operation and a unity power factor is succeeded in this procedure. Then, a current reference for the direct axis is set to zero and a current reference for the quadrature axis is adjusted for negative and positive reference current values. Thus, the voltage and current waveforms of the grid have a phase difference and reactive power is created. Besides, the measured inverter output voltage is directly proportional to its CCA value and the measured voltage has also visible high-frequency switching ripples compared to its CCA value. As a consequence, the obtained results indicate that a highly sensitive grid-connected inverter with a single-phase structure is designed to against the current variations. With the further adoption of renewable resources, grid-connected inverters will play a critical role not only in academic research but also in industrial areas.

## DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical commitee permission and/or legal-special permission.

## AUTHORS' CONTRIBUTIONS

**Mehmet Zahid EREL:** Performed the analysis and wrote the manuscript.

## CONFLICT OF INTEREST

There is no conflict of interest in this study.

## REFERENCES


[1] Kumar A. L., Alexander S. A., and Rajendran M., "***Power Electronic Converters for Solar Photovoltaic Systems***", Eds.: Academic Press, USA, (2021).

[2] Selamoğulları U. S., "Yenilenebilir Enerji Kaynaklarına Sahip Bir Evin Talep Karakteristiğine Uygun Bir İnverter Tasarımının İncelenmesi", ***Politeknik Dergisi***, 23(2): 257-265, (2020).

[3] Arıcı N. and Iskender A.,"Fotovoltaik Güneş Santrallerinde Şebeke Bağlantı Sorunları ve Çözümleri", ***Politeknik Dergisi***, 23(1):215-222, (2020).

[4] Keskin V. , Khalejan S. H. P. R. and Çıkla R. , "Investigation of the Shading Effect on the Performance of a grid-connected PV Plant in Samsun/Turkey", ***Politeknik Dergisi***, 24(2):553-563, (2021).

[5] Jana J., Saha H., and Das Bhattacharya K., "A review of inverter topologies for single-phase grid-connected photovoltaic systems", ***Renewable and Sustainable Energy Reviews***, 72:1256-1270, (2017).

[6] Kavya Santhoshi B., Mohana Sundaram K., Padmanaban S., Holm-Nielsen J. B., and P. K. K, "Critical Review of PV Grid-Tied Inverters", ***Energies***, 12:10, (2019).

[7] Bierhoff M., Soliman R., and J. R. E. C, "Analysis and Design of Grid-Tied Inverter With LCL Filter", ***IEEE Open Journal of Power Electronics***, 1:161-169, (2020).

[8] Cao N., Cao Y. J., and Liu J. Y., "Modeling and analysis of grid-connected inverter for PV generation", ***Advanced Materials Research***, 760: 451-456, (2013).

[9] Hossain M. N., Routh T. K., Yousuf A. H. B., Asasduzzaman M. M., Hossain M. I., and Husnaeen U., "Design and development of a grid tied solar inverter", ***2012 International Conference on Informatics, Electronics & Vision (ICIEV)***, Dhaka, 1054-1058, (2012).

[10] Bin Omar A. M. and binti Zainuddin H., "Modeling and simulation of grid inverter in grid-connected photovoltaic system", ***International Journal of Renewable Energy Research (IJRER)***, 4: 949-957, (2014).

[11] Abdar H. M., Chakraverty A., Moore D. H., Murray J. M., and Loparo K. A., "Design and implementation a specific grid-tie inverter for an agent-based microgrid", ***2012 IEEE Energytech***, Cleveland, 1-6, (2012).

[12] Mnider A. M., Atkinson D. J., Dahidah M., and Armstrong M., "A simplified DQ controller for single-phase grid-connected PV inverters", ***2016 7th International Renewable Energy Congress (IREC)***, Hammamet, 1-6, (2016).

[13] Behera P. K., Das S., and Pattnaik M., "Performance Comparison Between Bipolar and Unipolar Switching Scheme for a Single-Phase Inverter Based Stand-alone Photovoltaic System", ***2019 IEEE 16th India Council International Conference (INDICON)***, Rajkot, 1-4, (2019).

[14] Liserre M., Blaabjerg F., and Hansen S., "Design and control of an LCL-filter-based three-phase active rectifier", ***IEEE Transactions on Industry Applications***, 41: 1281-1291, (2005).

[15] Marandi D., Sowmya T. N., and Babu B. C., "Comparative study between unipolar and bipolar switching scheme with LCL filter for single-phase grid connected inverter system", ***2012 IEEE Students' Conference on Electrical, Electronics and Computer Science***, Bhopal, 1-4, (2012).

[16] Kjær S. B., "Design and control of an inverter for photovoltaic applications", ***PhD Thesis***, Institut for Energiteknik, Aalborg Universitet, (2005).

[17] Hyosung K. and Kyoung-Hwan K., "Filter design for grid connected PV inverters", ***2008 IEEE International Conference on Sustainable Energy Technologies***, Singapore, 1070-1075, (2008).

[18] Kantar E., Usluer S. N., and Hava A. M., "Design and performance analysis of a grid connected PWM-VSI system", ***2013 8th International Conference on Electrical and Electronics Engineering (ELECO)***, Bursa, 157-161, (2013).