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MPPT Yöntemi ile İki Aşamalı Üç Fazlı Şebeke Bağlantılı Fotovoltaik Sistem

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Öz

Bu çalışma, fotovoltaik (FV) sistem tarafından üretilen gücün, üç fazlı alternatif akım (AA) güç şebekesine maksimum verimle iki aşamada kontrol edilerek aktarılmasını incelemektedir. Tasarlanan FV sistemi ile güç kararlılığını sağlamak için kaynaktan yüksek verimle alınan enerjinin maksimum güç noktası izleme (MGNT) yöntemi kullanılarak ağa aktarılması amaçlanmaktadır. Ayrıca ikinci bir kontrol mekanizması ile evirici çıkışındaki akım anlık olarak kontrol edilmekte ve üretilen gücün gerilim değeri sabit tutulmaktadır. Bu kontrol sistemi sayesinde güneş enerjisi, elektrik enerjisi üretiminden elektrik şebekesine aktarılmasına kadar kontrol altında tutulmuştur. Üretilen gücün kalitesinin tahmin edilebilmesi için bilgisayar ortamında yapılan simülasyonlar sonucunda FV sistem çıkışındaki akımın toplam harmonik bozulma (THB) oranı belirlenmiştir. Simüle edilen FV sisteminin, farklı güneş ışınım seviyeleri değerlerine göre, şebekeye aktarılacak gücün voltaj değerini istenilen seviyede sabit tutma eğiliminde olduğu ve maksimum güç üretimi sırasında THB değerinin yüzde üçün altına düşürüldüğü görülmektedir.

Anahtar Kelimeler
Fotovoltaik Sistem; Yenilenebilir Enerji Kaynakları, Maksimum Güç Noktası Takibi; DC-DC Çevirici; DC-AC Evirici; Güç Şebekesi

Two-Stage Three-Phase Grid-Tied Photovoltaic System with MPPT Method

Abstract

This paper examines the transfer of the power generated by the photovoltaic (PV) system to the three-phase alternating current (AC) power grid with maximum efficiency by controlling in two stages. With the designed PV system, it is aimed to transfer the energy received from the source with high efficiency to the network by using the maximum power point tracking (MPPT) method in order to ensure power stability. In addition, with a second control mechanism, the current at the output of the inverter is instantly controlled and the voltage value of the generated power is kept constant. Thanks to this control system, solar energy has been kept under control from electrical energy generation to its transfer to the power grid. In order to predict the quality of the generated power, the total harmonic distortion (THD) rate of the current at the output of the PV system was determined as a result of the simulations made in the computer environment. It is seen that the simulated PV system, according to the values of different solar radiation levels, tends to keep the voltage value of the power to be transferred to the grid constant at the desired level and that the THD value has been reduced below three percent at the time of maximum power generation.

Keywords
Photovoltaic System; Renewable Energy Sources; Maximum Power Point Tracking; DC-DC Converter; DC-AC Inverter; Power Grid

1. Introduction

Today, the increasing demand for energy and the decrease of fossil fuels directs humanity to use renewable energy resources (RES) more effectively. By extending the use of resources such as solar energy, wind energy and hydroelectric energy we can obtain electrical energy without spending a resource and the harmful effects of power plants or nuclear power plants that use fossil fuels during energy production are avoided (Libo et al., 2007; Durusu et al., 2020).

While wind and hydroelectric energy have had a large installed capacity among renewable energy sources in the last decade, in recent years, PV systems continue to increase their capacity increase year by year, with the effect of easy installation and low maintenance costs, as well as government incentives (Bllabjerg et al., 2006). According to Irena data, as of 2020, the total installed PV power in the world is 707,494 MW (Irena data).

In addition, as a result of the global warming, which has increased its effect in recent years, the increase of the radiation effect all over the world makes the use of solar energy much more important (Trenberth et al., 2009).

PV systems can basically be considered as two main groups. The first of these are standalone systems, which are suitable for individual use. In these systems, a battery or battery group stores the energy absorbed during the day and feeds the loads connected to the system when necessary. The other is grid-connected PV systems that transfer the energy absorbed by the panels directly to the power grid (Isen et al., 2021).

In both types of PV systems, the voltage value at the output of the PV panel will vary continuously with the effect of weather conditions and non-linear loads in the system. Feeding the battery for standalone systems with this unregulated voltage will reduce the life of the battery (Gelen et al., 2019) and will also cause synchronization problems in systems connected to the grid. If this synchronization problem is not resolved, it may lead to unstable behavior and even failure in the power grid (Rekik et al., 2015).

Power electronic circuits have a critical importance in PV systems in order to regulate the voltage at the panel output and to operate the system stably (Libo et al., 2007). In addition, the V-I curve of the PV system can be created by considering the panel characteristics according to the estimated data of solar irradiance level and temperature (Kumar et al., 2018). An algorithm called Maximum Power Point Tracking (MPPT), which will switch the power electronics circuit, will always try to reach the peak point of the V-I curve so the transferred power be maximum at any time.

In order to increase the efficiency of PV systems, many MPPT methods have been presented in the literature. Apart from traditional methods such as perturbation and observation (P&O), incremental conductance (IC) (Putri et al.,2015), there are also new intelligent MPPT methods such as optimum gradient control (Gui et al., 2012), fuzzy logic controller (Prasad et al.,2017; Algarin et al., 2017), type-2 fuzzy logic controller (Kececioglu et al., 2020), neural networks (Messalti et al., 2017). (Cetin et al., 2018) presents a different perspective with this study, by controlling the inverter instead of the converter, unlike other methods. According to the literature, P&O method and IC method are frequently used in solar energy systems due to their success, easy application and affordable prices. Although they have not reached as high efficiency as the new intelligent control methods, they are still advantageous and valid methods in many ways (Bendib et al., 2015).

In this study, it is aimed to design a solar power plant with a total rated power of 100 kW while working at full capacity. In this case, it is aimed to keep the solar energy harvested by the selected number of solar cells at the desired voltage value with the direct current-direct current (DC-DC) converter controlled by the MPPT method. This voltage value determined according to cell parameters enables the designed system to produce maximum power for variable solar radiation levels. A second control method is a pulse width modulation (PWM) loop that modulates the current at the DC-AC inverter output. Thus, it allows the generated energy to be transferred to the power grid in a synchronous manner by keeping the DC bus voltage constant. The parallel operation of these two separate control systems constitutes a two-stage cycle.

2. Materials and Method

2.1 Photovoltaic Model

Photovoltaic (PV) system is a structure formed by many solar cells. Solar cells can convert the light falling on it directly into electrical energy with the help of a circuit. It is possible to increase the voltage values by connecting the modules formed by the solar cells in series. These series modules can be called as PV-strings. Also, by combining PV-strings in parallel, PV-arrays can be created by increasing the current value while keeping the voltage value constant. Thus, it is possible to increase the nominal power of the PV system to the desired level (Qun et al, 2008; Hussaini et al., 2017).

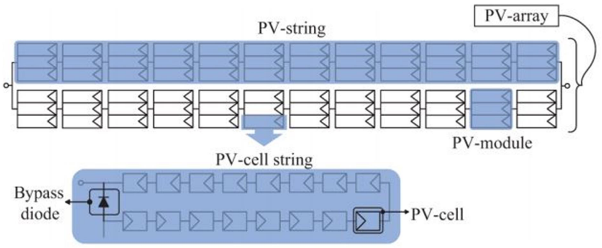

Figure 1. Pv-array (Psarros et al.,2015)

As seen in Fig.1, the total voltage value of the series can be calculated by summing the voltage values of the modules connected in series. Therefore, the required number of modules can be determined for this system, which is designed with a nominal power of 100 kW. It is possible to determine the characteristic V-I curve for a single PV-module used in the design with the help of some parameters. It is possible to calculate the power by using the determined voltage and current values. The voltage value corresponding to the maximum power point (MPP) can be determined from the V-P curve defined according to calculation. The voltage value corresponding to the peak value of the created V-P graph, in other words, the voltage value corresponding to the maximum power value that will operate with the highest efficiency of the system is the value at which the system aims to work constantly. The MPPT algorithm will control this value in small time intervals and try to keep it at the desired level instantly.

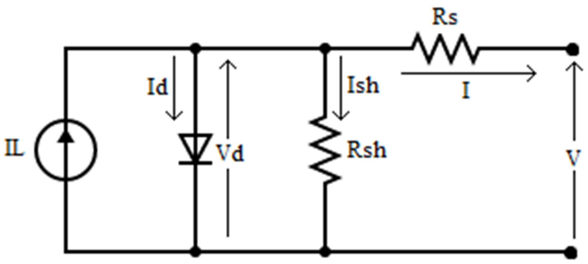

Figure 2. The equivalent circuit of a solar cell

$$I = I_L - I_d - V_d/R_{sh} \tag{1}$$

$$V_d = \mathrm{V} - IR_s \tag{2}$$

$$I_d = I_0\left[\exp\left(\frac{qV_d}{\mathrm{nkT}}\right) - 1\right] \tag{3}$$

$$I = I_L - I_0\left[\exp\left(\frac{q(V + IR_s)}{\mathrm{nkT}}\right) - 1\right] \tag{4}$$

Where I is output current (A), V is output voltage (V), I_d is average current through diode (A), V_d is the voltage across the diode (V), I_L is light generated current (A), I_0 is diode saturation current (A), R_{sh} is shunt resistance of the cell, R_s is the series resistance of the cell, n is diode ideality factor, k is Boltzmann's constant = 1.3806e-23 J/K, q is Electron charge = 1.6022e-19 C, T is cell temperature (K).

In the circuit diagram shown in Fig. 2, the current source indicated as I_L represents the solar cell. Using Eq. (1), the current generated by PV cell can be calculate. When Eq. (1) is expressed again using terms in Eq. (2) and (3) current corresponding to the voltage values of the power absorbed from the cell and transferred to the output diode can be calculating by using Eq. (4). Thus, a V-I plot can be obtained for the solar cell's output. Using the obtained current and voltage value, the V-P graph is created to determine the MPP.

Table 1. Model Parameters

Module Parameters	**Values**
Light-generated current (IL)	7.8645 A
Diode saturation current (I0)	2.9273e-10 A
Diode ideality factor	0.98119V
Shunt resistance Rsh	313.0553 ohm
Series resistance Rs	0.39381 ohm

Table 2. Module Data

Module Data	**Values**
Maximum Power	213.15 W
Cells per module (Ncell)	60
Voltage at maximum power point (Vmp)	29 V
Current at maximum power point (Imp)	7.35 A
Open circuit voltage (Voc)	36.3 V
Short circuit current (Isc)	7.84 A
Temperature coefficent of Voc (%/deg.C)	-0.36099
Temperature coefficent of Isn (%/deg.C)	0.102
Temperature of cell (Tcell)	25 deg.C

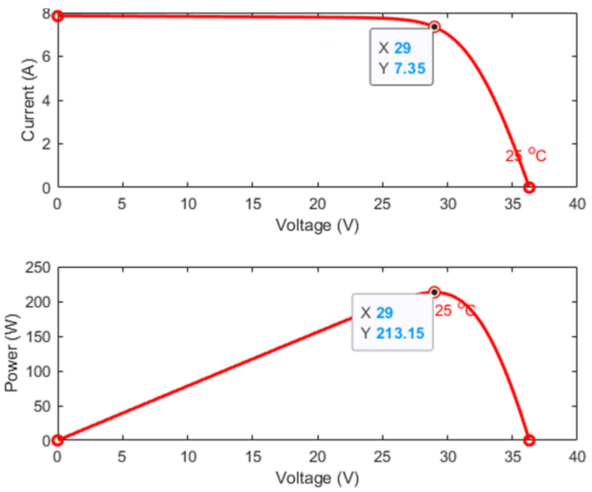

Figure 3. V-I and V-P characteristic curves of a solar module at 25 deg.C temperature and 1000 W / m ^ 2 irradiance level

The V-P curve obtained by using the module parameters in Table I. can be seen in Fig. 3. The voltage and current values for MPP, which is the point where this curve reaches its peak value, have been determined as 29 V and 7.35 A. Thus, the power of a module that will operate under 1000 W / m ^ 2 irradiance level and 25 ° C temperature has been determined as 213.15 W. Also, the MPP for different temperature values are determined in Fig 4. When the system is aimed to have a total power of 100 kW and the temperature determined for the system designed in this paper is 25 ° C so it will be sufficient to use 23 parallel strings consisting of 20 parallel modules each. Therefore, the voltage value for MPP of the PV-array is determined as 580 V.

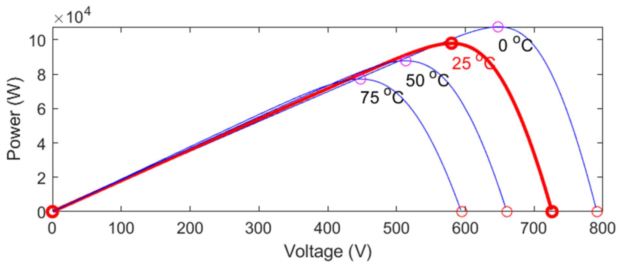

Figure 4. V-I and V-P characteristic curves of a solar module at 25 deg.C temperature and 1000 W / m ^ 2 irradiance level

2.2 MPPT Method

MPPT system periodically receives output voltage and current data from the PV module. Thus, the power data calculated by the P&O algorithm is compared with the previous measurement. As it is stated in the flowchart in Fig 5. the new value of voltage changes according to the increases or decreases of the previous power and voltage values. For values below the MPP value, the output voltage is increased and this process go on until the new power reaches the MPP. If the MPP point is exceeded, the perturbation will work in reverse and try to reach the MPP in the same way. Thus, the MPPT algorithm consist of all possibilities for changes in voltage and power values and they all end up with reaching to MPP.

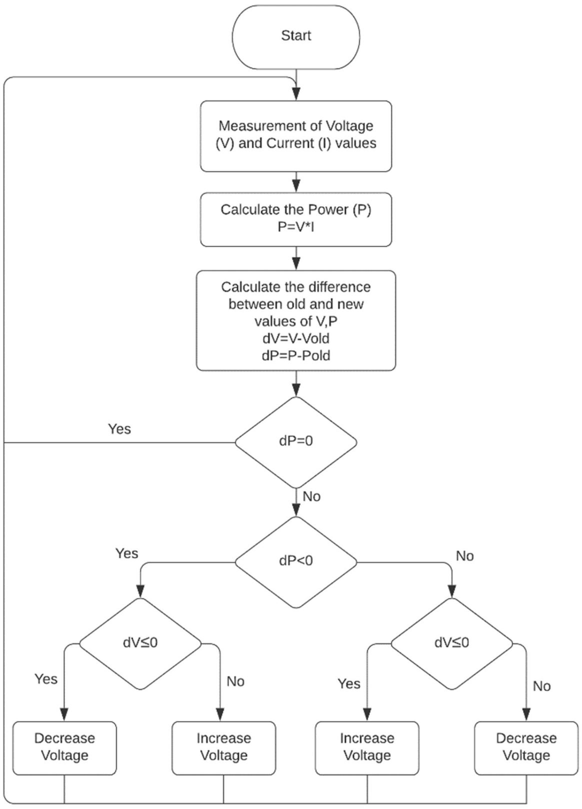

Figure 5. Flowchart of P&O algorithm

MPPT system periodically receives output voltage and current data from the PV module. Thus, the power data calculated by the P&O algorithm is compared with the previous measurement. As it is stated in the flowchart in Fig 5. the new valued of voltage changes according to the increases or decreases of the previous power and voltage values. For values below the MPP value, the output voltage is increased and this process goes on until the new power reaches the MPP. If the MPP point is exceeded, the perturbation will work in reverse and try to reach the MPP in the same way. Thus, the MPPT algorithm consists of all possibilities for changes in voltage and power values and they all end up with reaching to MPP.

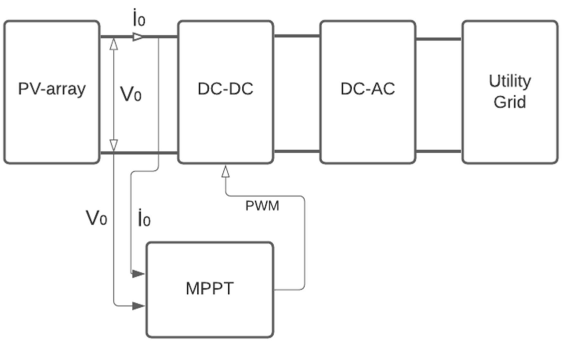

Figure 6. Block diagram of the PV system with MPPT algorithm

2.3 DC-DC Boost Converter

DC-DC boost converters are power electronic circuits that step up the DC voltage to desired higher level. As can be seen in Fig.7, the boost converter circuit consists of inductor, diode, capacitor and semiconductor device for switching operation. By electronically switching the DC voltage from the source at certain intervals, the output voltage can be regularly increased to the desired level by changing the current direction between the inductor and the capacitor. In this paper, insulated gate bipolar transistor (IGBT) is used as the switching device and the switching duty cycle is determined by the MPPT algorithm. If it is necessary to decrease the voltage level to reach MPP, the algorithm decreases the duty cycle, if the voltage level is to be increased, the duty cycle is increased. The duty cycle obtained by the algorithm is converted into a PWM signal by modulating it with a switching frequency of 5000 Hz.

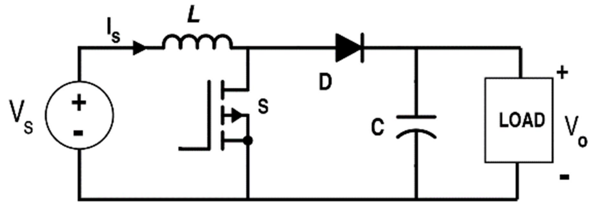

Figure 7. Boost converter circuit diagram (Kumar et al., 2017)

As a result, it is possible to determine the inductance and capacitance values required for the inductor and capacitor of a boost converter with an input voltage of 580 V and an output voltage of 800 V.

$$V_0 = \frac{V_s}{1-D} \tag{5}$$

$$L_{min} = \frac{D(1-D)^2 R}{2} \tag{6}$$

$$C \geq \frac{D}{R(\Delta V_o / V_o) f} \tag{7}$$

Where V_0 is output voltage, V_s is input voltage, D is duty ratio, f is switching frequency, $\Delta V_o/V_o$ is voltage ripple ratio. The output resistant (R) can be express as $\frac{V_o^2}{P}$ since there is no directly connected load in the output of the boost converter. Minimum inductance value for continuous current and minimum capacitance value to limit the required voltage ripple percentage can determine from Eqs. (6) And (7) (Hart, 2010).

In order to reduce the fluctuation in output current, 0.1 mH selected for the inductance. For the capacitor, the minimum capacitance value is calculated as approximately 18 mF. With the boost converter circuit working in coordination with the designed MPPT algorithm, the power received from the PV system is transferred to the DC - AC inverter in order to be transmitted to the alternating current grid with maximum efficiency.

2.4 DC-AC Inverter

DC-AC inverters are used to transfer the DC power generated in the PV system to the AC power grid. As shown in Fig.8, three-phase grid-tied DC-AC inverter consist of two capacitors at the DC side and six power switches with six diodes connected them at the AC side (Erfidan et al., 2008).

The current converted to AC by the inverter must ensure synchronization before it is transferred to the grid. Therefore, a phase locked loop (PLL) method detects the phase angle of the grid voltage. Also, the output current of the inverter compares with the reference current. This error generates control a signal with help of a proportional-integral (PI) controller. This signal transform from a dqo rotating reference to a three-phase (abc) signal with the help of angular position of rotating frame mentioned before. The obtained three-phase signal modulate to PMW signal to provide switching signal for IGBT power switches of the DC-AC inverter (Phap et al., 2017).

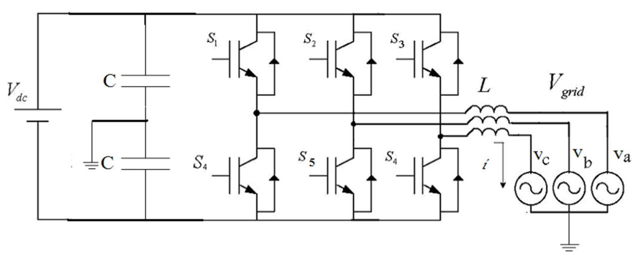

Figure 8. Three-phase inverter circuit diagram (Ghani et al., 2010).

The fundamental problem of nonlinear power electronic systems such as inverters in connecting to the grid is harmonic distortion (HD). As a result of connecting systems with regular fluctuations such as PV to the grid, deterioration in energy quality occurs due to the stress applied to the power in the grid. Therefore, this problem can be reduced by filtering the generated powers before they are transferred to the grid. In this paper, a L-filter, which is a passive element, was placed between the inverter output and each phase to reduce HD. It is very important for the stability of the power systems to keep the THD ratio of the power under control and to ensure that it is as low as possible. It is possible to determine the inductance of the L filter to be used for this study.

$$L_f = \frac{0.1U^2}{2\pi f P_{1-phase}} \tag{8}$$

The inductance of the L filter was calculated as 1.4 mH, based on the value calculated using Eq. (6). Thanks to this filter added to the system, THD was reduced and the stability that started with the power generation in the PV system was maintained during the transfer of the generated power to the network (Güler et al., 2019).

3. Results

Grid-connected PV system prepared in MATLAB & Simulink environment is shown in Figure 9. During the simulation, the cell temperature was fixed at 25 ° C. In addition, solar radiation data from the PVGIS-SARAH database created by the Photovoltaic Geographical Information System (PVGIS) were used during the simulation. As seen in Figure 10, the daily radiation value of clear sky for one day from July 2019 for Afyonkarahisar province in Turkey varies between 0 and 1000 W / m ^ 2. These two signals applied for 24 seconds to represent a day constitute the inputs of the PV panel system.

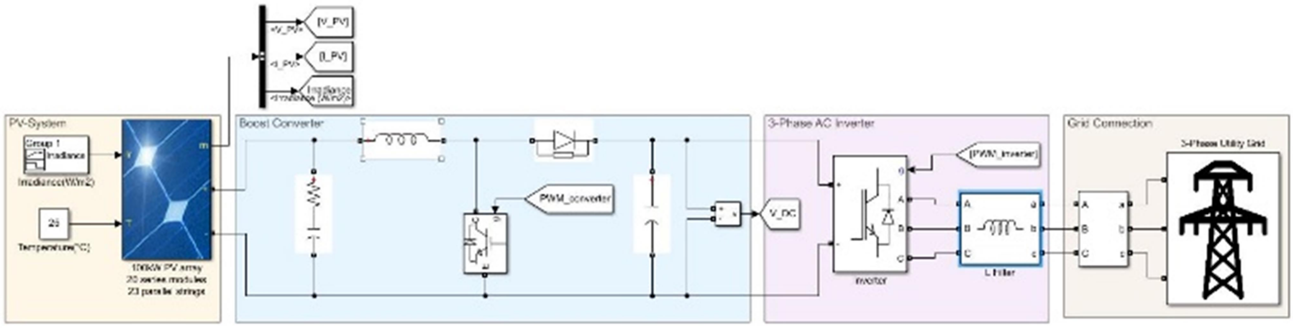

Figure 9. Grid tied PV system Simulink model.

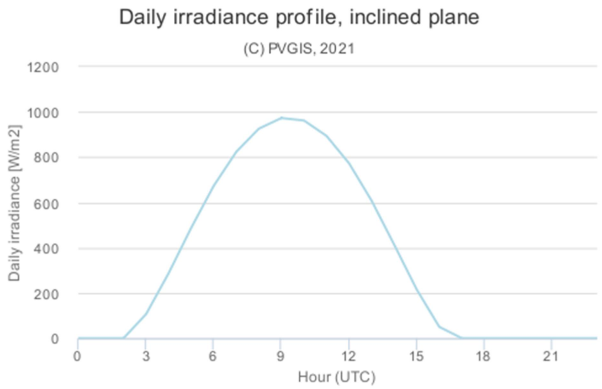

Figure 10. Daily irradiance graph of a province.

According to PVGIS-SARAH data in a 24-hour period, one-day radiation level for the province of Afyonkarahisar for the month of July (Huld et al., 2012).

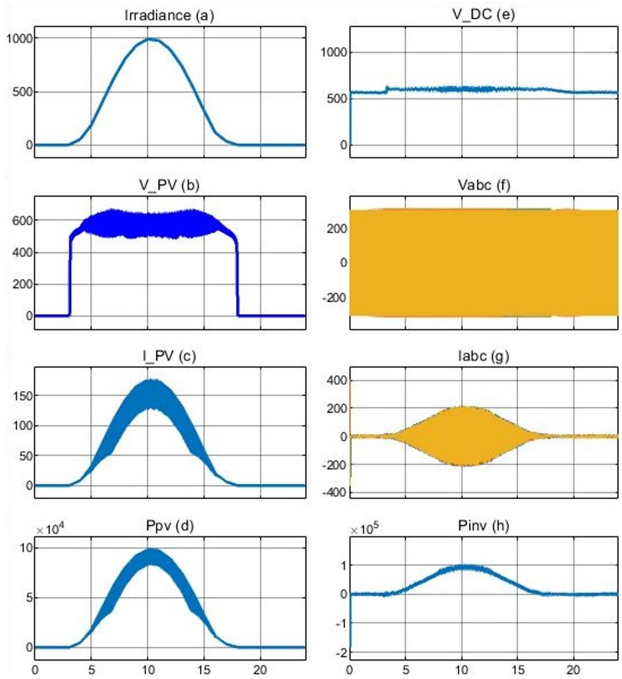

Figure 11. Simulation results, a: Daily radiation level, b: PV voltage, c: PV current, d: Transferred power from PV, e: DC bus voltage, f: 3-phase AC grid voltage, g: 3-phase current transferred to the grid, h: Power transferred from inverter to grid.

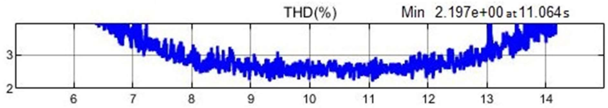

Figure 12. THD (%) value for current represent to grid.

Fig.11 (a) represents the data of the radiation level used in the simulation. Fig. 11 (b) refers to the voltage of the energy absorbed by the PV system according to the MPPT algorithm. Fig.11 (c) refers the current transferred from PV system. It is possible to reduce the fluctuation in the current by increasing the value of the inductance used in the converter. Fig.11 (d) refers to the power generated frow the PV-array. Although the power value chance with the radiation level as expected, the PV system can produce up to 100 kW of power at maximum capacity. Fig.11 (e) represent the voltage level of DC busbar. Since the capacitor in the DC bus is empty at the beginning and the radiation level is 0, the PV system has been fed from the grid. Later, by increasing the radiation the DC bus voltage in reached the reference voltage 600V and kept constant. Fig.11 (f) represent the grid voltage which 310 V peak value and 50 Hz frequency. Fig.11 (g) represent the current which transferred to grid. Fig.11 (h) represent the total active power transferred to grid. Fig.12 refers the THD value of the transferred current. As seen in the figure, the total distortion is below 5% at the 5-15 seconds time interval when the power generation is high. When the power generation reaches the highest value, THD declined to 2.197%. This refers to the quality of the power transferred from the designed system to the network.

4. Discussion and Conclusion

In this paper, the connection of the PV system to the three-phase grid and the control methods consisting of two stages are presented. It has been determined that an MPPT control algorithm to be added to the PV system greatly increases the efficiency of the system, so that the power generation is at the highest level for each radiation level. Also, with the help of a current-controlled inverter, the synchronization problems during connection to the grid were overcome by keeping the output current constant. In addition, the HDs generated by the use of power electronics systems was reduced with the help of a filter. As can be observed from the simulation outputs, the two-stage PV system can both use solar energy efficiently in power generation and transfer it to the 3-phase grid without having synchronism problems. In this context, although the proposed PV system is open to development and improvement, it can still be actively used in projects due to its being economical, having the advantages of RESs and its very stable operation.

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