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DESIGN AND PERFORMANCE ANALYSIS OF AN ON-GRID PHOTOVOLTAIC POWER SYSTEM UNDER IRAQI SOLAR CIRCUMSTANCES

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Abstract: Solar photovoltaic (PV) power systems are one of the best renewable energy sources in Iraq due to longer daily and annual sunshine hours. In this paper, an on-grid PV power system is designed to operate in parallel with the local grid (only during sunshine hours) to either supply household appliances, or to back-feed the grid when the output power of a PV system is greater than household demand. The proposed system includes a PV array with maximum power point tracking (MPPT) algorithm, a boost converter, an inverter and an LC filter. The main challenge of designing the proposed system is the ability to combine the power electronic converters with the corresponding control method to achieve best performance. A current controller and a voltage controller are proposed for respectively achieving maximum power and controlling AC voltage. The aim of this research is to demonstrate the performance analysis of on-grid PV array system under real daily irradiance for Baghdad during June. The simulation results show that in case of using MPPT algorithm, the percentage power yield from PV array system is 95%, while in case without MPPT algorithm, it is 38%. In addition, the waveform of load current is sinusoidal with low total harmonic distortion (THD), i.e. 0.67%.

Keywords: *Photovoltaic power system, Boost converter, Grid-connected inverters, Voltage mode controller, Current mode controller*

تصميم وتحليل اداء نظام توليد كهروضوئي مربوط بالشبكة الكهربائية تحت ظروف الطقس العراقية

الخلاصة: تعتبر انظمة توليد القدرة الكهربائية باستخدام الالواح الكهروضوئية من افضل مصادر الطاقة المتجددة في العراق وذلك لطول ساعات الاشعاع الشمسية اليومية والسنوية. في البحث الحالي، تم تصميم نظام توليد كهروضوئي مربوط بالشبكة الكهربائية الوطنية وبدون استخدام وحدات خزن (بطاريات) ويمكن الاستفادة من النظام اعلاه لتشغيل احمال الانارة في بناية معينة او تغذية الشبكة الكهربائية عند وجود فائض في التوليد. تم تنفيذ خوارزمية تتبع القدرة العظمى لتحسين كفاءة المنظومة الشمسية وكذلك تم تثبيت فولتية الحمل حسب متطلبات الشبكة الكهربائية. من الضروري الاشارة الى انه تم تنفيذ النظام المقترح باستخدام بيانات عملية لمستويات الاشعاع الشمسي لمدينة بغداد خلال شهر حزيران ،وذلك لتحليل اداء نظام التوليد الشمسي عند حالات تشغيل حقيقية. لقد تم التوصل الى انه في حالة استخدام خوارزميات السيطرة فان القدرة الكلية المتناوبة المستحصلة من المنظومة هي تقريبا 95% مقارنة مع عدم استخدام خوارزميات السيطرة تقريباً 38%. اخيراً، لقد وجد ان نسبة التوافقيات في موجة تيار الحمل جدا قليلة وتساوي تقريباً 0.67%.

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1. Introduction

The use of renewable energy sources such as solar and wind energies can be extended to power residential and transportation applications due to environmental benefits. Nowadays, cheaper PV panels can be got from China but their performance affect with load voltage. For high voltage applications, the solar cell type must be considered, which is classified into three main groups: monocrystalline (single-crystal construction), polycrystalline (semi-crystalline), and amorphous silicon thin film [1]. Solar power systems can be categorized into two types: off-grid and on-grid. For off-grid solar power systems, the main electricity is only fed from PV panels and battery bank. These systems are suitable for remote area which are typically isolated from local grid. To maximize the power withdrawn from PV panels, maximum power point tracking (MPPT) charge controller is used by converting the variable DC voltage into maximum power point voltage. The important device in off-grid solar systems is the grid inverter which takes the DC power from both PV panels and batteries then converts it into AC power to directly supply the building. The inverters are classified into two types: grid tie inverter and normal inverter. The former one converts the solar power directly to main electricity. While, the latter one converts the DC power from both PV panels and batteries to local grid. Moreover, the latter one is also used for charging batteries [2].

For on-grid solar power systems, the building is fed from both local grid and a PV array in order to cover the consumer's own power demand and decrease electricity bills [3]. The PV panels are connected with a grid tie inverter that directly converts DC power into AC power (220 V, 50 Hz). For on-grid solar systems with a storage system, a MPPT charge controller, i.e. DC-DC converter, is used for charging the bank of batteries that connects with a separate inverter. The building in these systems can be supplied during power grid failure. The drawbacks of these systems are the big losses in power electronic converters and the high cost of maintenance. Basically, there are two types of grid tie inverter topologies: central inverters and micro inverters. Central inverter is the typical choice for high power solar systems.

Its efficiency is better than the other type, but it misses MPPT operation for each PV panel due to the fluctuations in atmosphere, e.g. shading and clouding. For micro inverters, each PV panel has its own small size inverter, which achieves optimal power conversion for each PV panel. For these inverters, if any PV panel is shaded or is not completely pointed to the sun, the total DC power is not highly affected [4].

Several studies have been conducted to design and analysis of on-grid solar power systems with or without energy storage devices. In [5],a grid-connected mini-solar power plant was designed and constructed. Each part of the solar plant is modelled and analyzed in order to estimate the behavior of the grid under various operating conditions [5]. In [6], power electronic circuits including a buck-boost converter with a full-brig inverter was presented to supply AC power with high power factor. In [6], the waveform of the output AC voltage was improved by selecting a high switching frequency for a buck-boost converter that operates in the discontinuous-current conduction-mode (DCCM) to avoid additional input inductor current controller. It is worth noting that most of on-grid PV inverters have been assessed by using unreal sun irradiance profile such as steps and ramps or triangle ramps. Although this test evaluation is easy to perform, it may not be representing the dynamic response of the system under actual conditions [7].

In this paper, an on-grid PV power system is designed for suppling a stable ac power without batteries. The system includes a PV array connected to grid via a boost-inverter and an LC filter. Both the array current and the boost DC voltage are respectively adjusted by controlling the duty cycles of a boost converter and modulation index of an inverter. The purpose of controlling the input current and DC voltage is respectively, to prevent the over-current passing through a PV array and to supply a constant ac voltage. The proposed PV array system is evaluated using Matlab/Simulink under real sun irradiances for Baghdad (e.g., using of measured sun irradiances over a day in June, 2014) as a case study.

2. Diagram of the Proposed PV Array Power System

Figure 1 shows the diagram of the proposed solar PV power system including a PV array, which supplies a grid via a boost-inverter. Two control signals (i.e., PWM1 for adjusting the array current at maximum power points, and PWM2 for controlling the output AC voltage) are essential to generate a reliable output power under real fluctuated irradiances. An LC filter is connected between an inverter and the local grid to achieve a sinusoidal AC voltage.

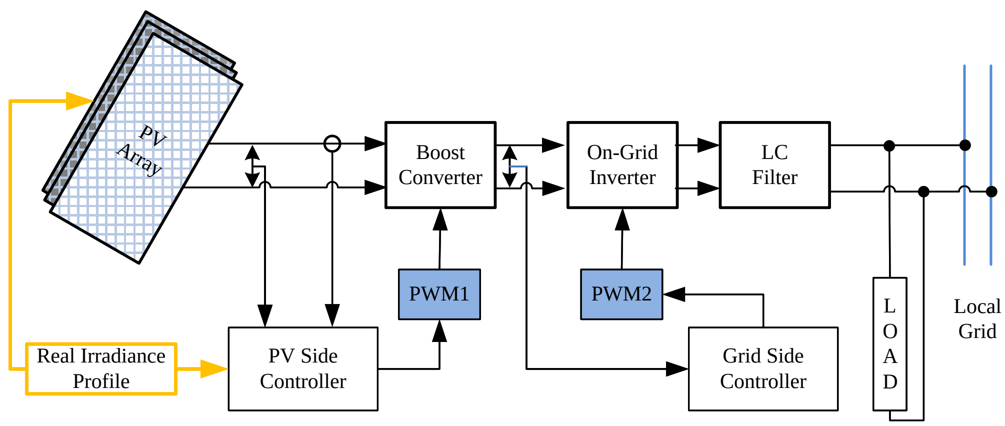

Fig. 1 Block diagram of the PV array power system.

3. Modelling and Design of the Proposed PV Power System

3.1. Real Irradiance Profile

In this paper, real sun irradiances were measured over a day in June, 2014 in Baghdad as shown in Fig. 2. The curve presents how the sun irradiance changes during sunshine hours. At 1:00 PM, the sun is at the peak point, the sun irradiance is approximately 960 W/m^2. But, at 8:00 AM and 6:00 PM, the sun irradiances are about

260 W/m^2 and 330 W/m^2, respectively. It is worth noting that the average sun irradiance is above 650 W/m^2, which is considered a sunny day [8].

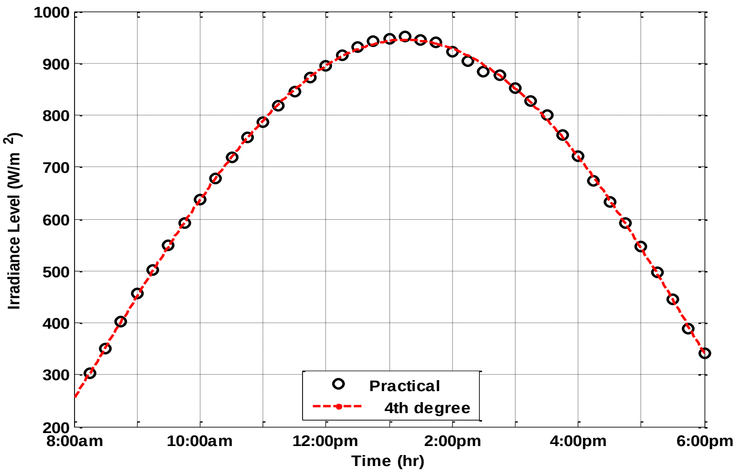

Fig. 2 Measured sun irradiances over a day in June, 2014 in Baghdad.

3.2. PV Array Simulator

PV panel is a device utilized to convert irradiance from the sun directly into DC power. Typically made of multiple silicon solar cells joint between glass and a backing material [1]. An embedded Matlab function is used to simulate a PV array. In literatures, a PV panel is simulated as a single diode exponential model, that provides fairly accurate current-voltage characteristics, since this model does not include the effect of parallel resistance, the I-V characteristics [9]. In this paper, a PV panel is simulated as a logarithmic model using Eqs. (1) - (3) [10]. This PV model requires four input parameters, which are listed in Table 1.

Table 1.Parameter values of a PV panel [11].

Parameter	Value
Open circuit voltage, V_{oc}	28.4 V
Short circuit current, I_{sc}	7.92 A
Voltage at maximum power point, V_{mpp}	22.8 V
Current at maximum power point, I_{mpp}	7.11 A
Type of Array connection and number of PV panels, N_{pv}	Series, 5

$$I_{PV} = \lambda I_{sc}[1 - C_1\{\exp(\frac{V_{pv}}{C_2 V_{oc}}) - 1\}] \qquad (1)$$

$$C_1 = (1 - \frac{I_{mpp}}{I_{sc}}) \exp(\frac{-V_{mpp}}{C_2 V_{oc}}) \qquad (2)$$

$$C_2 = \frac{(\frac{V_{mpp}}{V_{oc}} - 1)}{\ln(1 - \frac{I_{mpp}}{I_{sc}})} \qquad (3)$$

where V_{oc}, I_{sc}, V_{mpp} and I_{mpp} are described in Table 1; $C_1$and $C_2$are constants; λ is the per-unit sun irradiance at 1000 W/m^2.

Note that a PV panel can be also simulated as a dependent voltage-source, V_{pv}, by rearranging Eq. (1). It is clear from Eq. (4) that the PV current, I_{pv}, is firstly measured then entered to the proposed PV simulator [10].

$$V_{PV} = C_2 V_{oc} \ln\{\frac{1 + C_1 - (\frac{I_{pv}}{\lambda I_{sc}})}{C_1}\} \qquad (4)$$

Figure 3 shows a PV panel Simulink model based on an embedded Matlab function and a voltage-controlled source. It is worth noting that the upper limit of PV voltage does not exceed the open circuit voltage to protect the PV panel from overvoltage damage. Figure 4 shows the proposed PV array simulator, which continues five PV panels connected in series in order to increase the DC voltage and consequently reduce the size and cost of a boost converter.

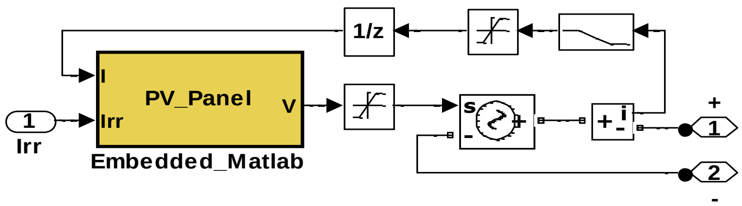

Fig. 3 Simulink model of a PV panel based on embedded Matlab function.

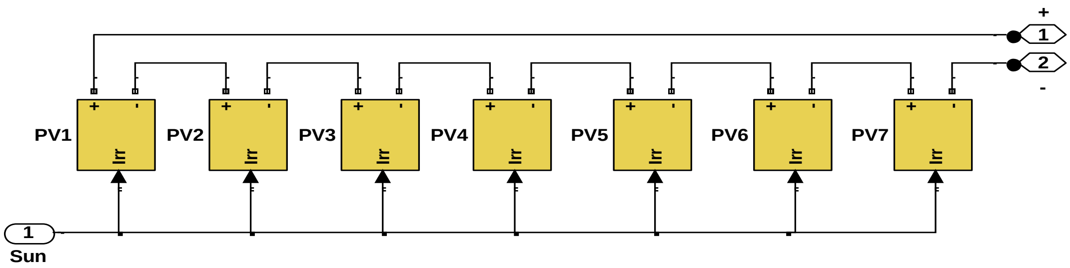

Fig. 4 PV power array.

3.3. Design of a Boost-Inverter with an LC Filter

The purpose of a boost-inverter is to convert DC power from PV array to a stable AC power with the following specifications: (i) implementing a MPPT algorithm (ii) constant voltage and frequency, i.e. 220 V and 50 Hz; (ii) high power factor and (iii) low current total harmonics distortion (THD). In this paper, a boost converter is designed for supplying a load of 1130 W at 311V. Due to variation of sun irradiance, theinput DC voltage of a boost converter is changed from 40 V to 155 V. Then the input DC voltage of an inverter mustbe also controlled in order to match the grid AC voltage [12]. To avoid switching losses, the switching frequency, f_{sw}, is set to 10 kHz for the initial design. If satisfy results are obtained with this frequency, the size and cost of a boost converter are decreased [13]. The variation in input inductor current, ΔI_{pv}, is chosen 50% less than of the average load current for all operating conditions. Furthermore, the perunit DC voltage ripple, ($\Delta V/V_{dc}$), is set less than 5%.

According to above initial design considerations, the minimum values of the boost inductor, L_{min}, and filter capacitor, C_{min}, are calculated via the following steps [12].

1. Calculating D with minimum PV voltage.

$$D = 1 - \frac{V_{pv}}{V_{dc}} \tag{5}$$

2. Calculating the average value of inductor current, I_{pv}.

$$I_{pv} = \frac{V_{dc}\, I_{load}}{V_{pv}} \tag{6}$$

3. Determining the minimum inductance, L_{min}.

$$L_{\min} = \frac{V_s\, D}{\Delta I_{pv}\, f_{sw}} \tag{7}$$

4. Repeating steps 1-3 for computing the maximum boost inductance, L_{max}, with maximum PV voltage.
5. Finally, calculating the minimum capacitance, C_{min}, with maximum duty cycle.

$$C_{\min} = \frac{D}{\left(\frac{V_{dc}}{I_{load}}\right)\left(\frac{\Delta V}{V_{dc}}\right) f_{sw}} \tag{8}$$

According to above steps, the minimum values of the inductance and capacitance are approximately 4.3mH and 25 μF, respectively. It is worth knowing that these values may achieve continuous mode operation. In this paper, a typical full-bridge inverter including four MOSFETs is used for DC to AC conversion. For getting a sinusoidal output voltage, the inverter frequency (i.e., the PWM frequency of the carrier signal) is increased.

Also, a sinusoidal filter (i.e., LC filter) is connected between an inverter and grid in order to obtain a smooth sine wave output voltage. As mentioned above, by increasing the inverter frequency, the cut-off frequency of an LC filter can be increased in order to decrease the size of filter inductance, *L*, and filter capacitance, *C*. Equation (9) is used for design an LC filter at 500 Hz and the values of *L* and *C* will present in Table 2.

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (9)$$

4. The Proposed PV Side and Grid Side Controllers

For interfacing a PV Array system with grid, a boost DC-DC converter and an inverter are essential with MPPT algorithm a DC voltage controller, which has several advantages such as: (i) improving the efficiency of a PV array system (ii) reducing the complexity of the PWM controller for an inverter and (iii) maintaining a high dynamic response at the AC side.

In this work, the PV current is adjusted by MPPT controller by adjusting the duty cycles of a boost converter. The key challenge in designing these controllers is generating the reference control signals under the variations of sun irradiance and load. Figure 5 and 6 show the block diagram of the proposed controllers.

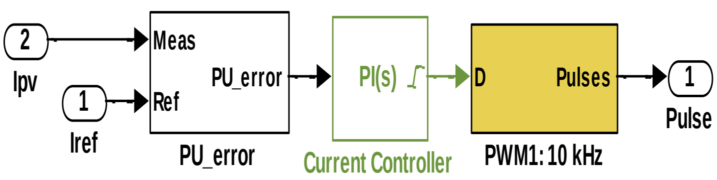

Fig. 5 PV side controller.

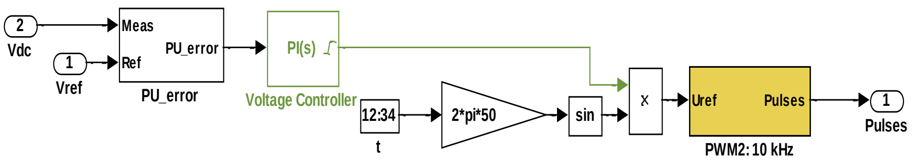

Fig. 6 Grid side controller.

As illustrated in Fig. 5, the reference currents are estimated from the proposed MPPT algorithm as shown in Fig. 7.

- Input: The sun irradiance via a light sensor, the array current I_{pv} and array voltage V_{pv}.
- Output: The reference PV array current I_{mpp}.
- Task: Estimate the reference currents under the variation of sun irradiance.

1. Initialization: $I_{ref}(k)=I_{pv}(k)$.
2. Computethe perunit irradiance factor K_{irr}.
3. Compute the amount of current of a controlled current source that connects with the exact PV array model (Eq. 1) using the practical parameters listed in Table 1: $I_{ref}(k) = I_{mpp} * K_{irr}$
4. Find the perunit current error: $E_i(k)=[I_{ref}(k) - I_{pv}(k)]/ I_{ref}(k)$.
5. Compute the duty cycle $D(k)$ by adjusting $E_i(k)$ via a PI controller.
6. Bounce the duty cycles between 0.01 to 0.9.
7. Compute the power error: $E_p(k)=P_{ref}(k) –[I_{pv}(k)*V_{pv}(k)]$
8. If $| E_p(k)| <\varepsilon$, return to 2.
9. If$E_p(k) < 0$, decrease the reference current, Else increase the reference current.
10. End.

Fig. 7 The proposed MPPT algorithm.

5. Analysis of Simulation Results

In this section, the simulations are conducted in order to validate the effectiveness of the proposed controller under Iraqi sun irradiances (see Fig. 2). The proposed PV array power system is implemented in Matlab/Simulink using the Simulink power system library as shown in Fig. 8.

Note that voltage and current sensors are applied to obtain (i) the array DC voltage and current; (ii) the boost DC voltage. The simulation parameters are summarized in Table 2.

Table 2. Parameter values.

Parameter	Value
Boost inductance, L, and resistance	4.3mH, 1 mΩ
DC-link capacitance, C	25μF
Filter inductance, L_f, and resistance	10 mH, 1 mΩ
Filter capacitance, C_f	10 μF
Load resistance, R	85.6Ω
Boost switching frequency, f_{sw}	10 kHz
Inverter frequency, f_{inv}	10 kHz
Sampling period, T_s	1 μsec

5.1. Performance of DC Side

DC side includes both a PV array and a boost converter. As mentioned above, the array current should be controlled to follow reference currents and must be kept less than the short-circuit current of a PV array. The reason is to prevent overcurrent damage. Figures (9) and (10) show respectively daily PV array current and voltage waveforms.

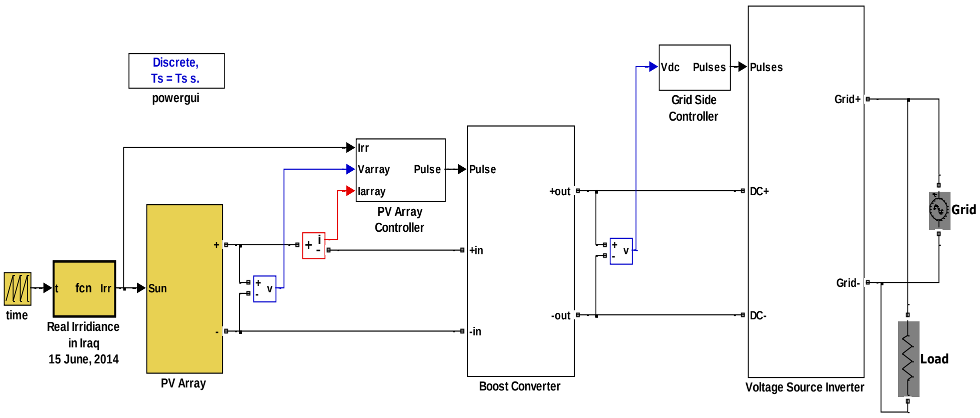

Fig. 8 Simulink model of PV array system with controllers.

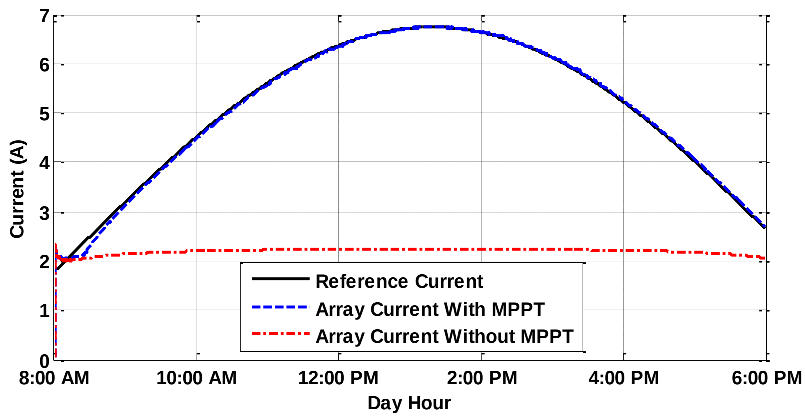

Fig. 9 Daily PV array current.

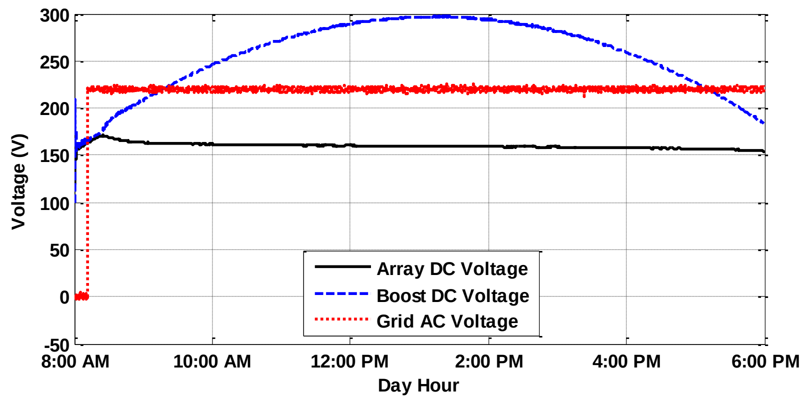

Fig. 10 Daily voltage waveforms.

Note that in case of using MPPT algorithm, the array current is very close to reference current and less than array short circuit current. As seen in Fig. 10, the RMS grid voltage is close to 220 V.

5.2. Performance of AC Side

AC side includes an inverter and an LC filter. The quality assessment of a PV array power is mainly based on: (i) keeping the output AC voltage and frequency constant; (ii) minimizing the THDs of load current. The FFT analysis of load current is shown in Fig. 11 without using MPPT algorithm and Fig. 12 with using MPPT algorithm. It is clear that the THD of load current (with using MPPT algorithm) at inverter frequency of 10 kHz meet the limits proposed in IEEE standard, i.e. THD should be no higher than 5%.

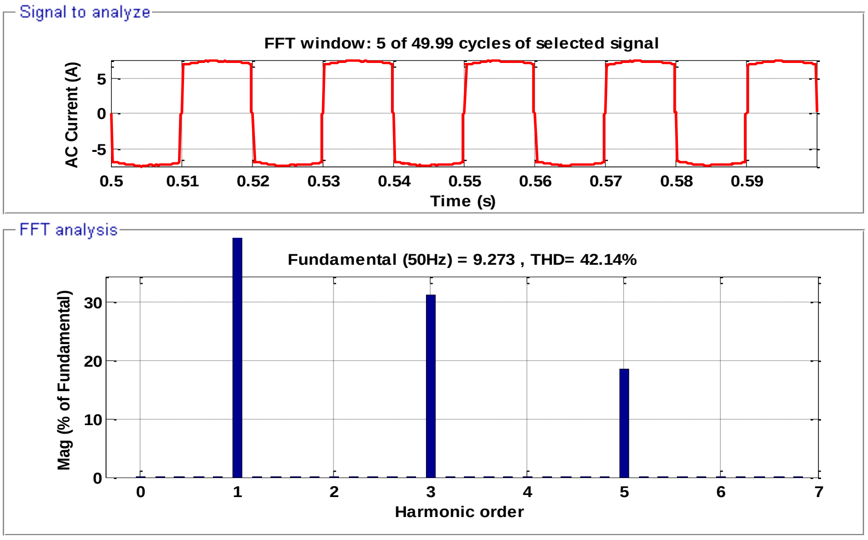

Fig. 11 FFT analysis of load current without an LC filter.

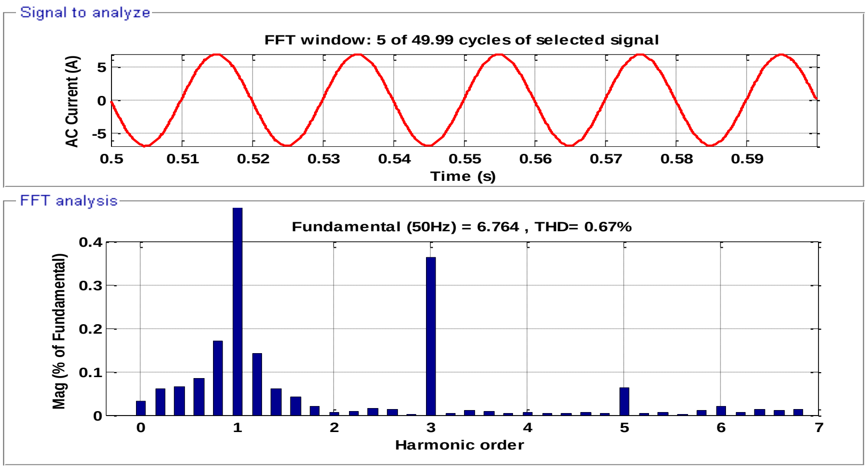

Fig. 12 FFT analysis of load current with an LC filter.

5.3. PV Array Power

Figure 13 shows the nominal and the total AC power (with and without MPPT algorithm) under real Iraqi sun irradiances (as previously illustrated in Fig. 2). It is seen that the total ACpower (with using MPPT algorithm) is close to nominal PV array power. The percentage power yield from the PV array system at 1:00 PM is listed in Table 3.

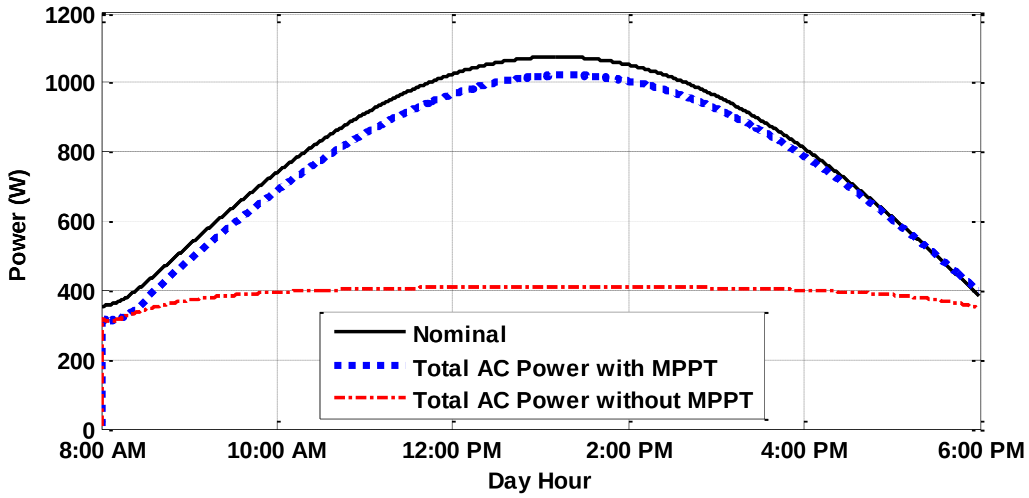

Fig. 13 Daily total AC power.

Table 3.Percentage power yield from the PV array system.

Day Hour	With MPPT	Without MPPT
1:00 PM	95%	38%

6. Conclusions

This paper demonstrates the performance of an on-grid PV array power system under real sun irradiances in Iraq as a case study. A PV array is connected with a boost inverter in order to control the array current and load voltage (as well as frequency). A PV side controller and a grid side controller are implemented for improving the power performance of the proposed PV array system using real sun irradiance for Baghdad during June. It is found that in case of using the proposed MPPT algorithm, the percentage power yield from the PV array system is 95% in comparison without using MPPT algorithm is 38%. In addition, the current THD is about 0.67% with using LC filter. While without using LC filter is 42.14%.

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