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A Proposed PVPS Simulink Model Suitable for Direct Coupled AC Loads

نموذج سميولينك مقترح لتمثيل منظومة كهروضونية تغذى بشكل مباشر أحمال تيار متردد

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ملخص البحث:

من أجل تطوير منظومة كهروضونية تحتاج إما أن يتم اختبارها معمليا أو عمل محاكاة لها باستخدام أحد برامج المحاكاة مثل برنامج سميولينك. وفي الحقيقة فإن عملية المحاكاة تزيد من فهم أداء المنظومة الكهروضونية، ويمكن دراسة وتحليل تأثير عديد من العوامل على المنظومة من خلال محاكاة النموذج المقترح.

بناءً على ذلك يقدم هذا البحث نموذجا مقترحا مؤسس على برنامج السميولينك لمنظومة كهروضونية تغذى بشكل مباشر حمل تيار متغير. وهذا النموذج المقترح يتكون من مولد كهروضوئي ، ومحول تيار مستمر- مستمر ، ومتحكم نقطة أقصى قدرة ، عاكس (تيار مستمر- تيار متغير) ومجموعة مكثفات تعمل كرابط تيار مستمر وفى نفس الوقت كنظام تخزين للطاقة. وهذا الرابط يعمل على حفظ الاتزان بين التيار المستمر والتيار المتردد المغذى للحمل. وقد تم تصميم مكونات النظام الداخلية وتطوير النموذج المقترح فى بيئة ماتلاب- سيميولينك وتحقيق التصميم الأمثل لذلك. وقد تم أخذ القياسات بعد كل مرحلة من النظام للاختبار والتحقق من التصميم. ويقدم البحث نتائج عملية المحاكاة والتى تم تحليلها واستخدامها لتحقيق والتأكد من أن النظام المقترح يمكن تطبيقه لتمثيل ودراسة أداء منظومة كهروضونية تغذى حمل تيار متغير.

Abstract

In order to develop a PV system, it needs to be either tested in a laboratory based power system model or to be simulated using a simulation program like Simulink. In fact, PV simulations provide good understanding of PV performance. The effect of many PV parameters can be studied and analyzed by simulating the proposed model. This paper presents a proposed PVPS Simulink model suitable for direct coupled PV-AC load system. The model consists of PV generator, DC-DC converter, maximum power point controller, DC-AC inverter and capacitor bank DC link as energy storage system. The DC link is used also to maintain balance between the DC power and the AC power transferred to the load. The entire system components are designed and a Matlab-Simulink model is developed and simulated to validate the optimum design of them. Measurements are taken at each stage of the system to test, verify and validate the design. Simulations results verify the functionality of PV generation system with a resistive AC load.

Key words: PV model, dc-dc converter, dc-ac inverter model, maximum power point tracker

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1. Introduction

Renewable energy resources are an increasingly important part of power generation in the new millennium. Besides assisting in the reduction of the emission of greenhouse gases, they add the much-needed flexibility to the energy resource mix by decreasing the dependence on fossil fuels [1]. Photovoltaic (PV) systems are ideally suited for stand alone and distributed resource applications. PV systems produce DC electricity when sunlight shines on the PV array, without any emissions. The DC power is converted to AC power with an inverter that can be used to power AC loads. This paper deals with modeling and design of a direct operation of a PV generation system feeding an AC load. The proposed system consists of a PV generator, a power electronic conditioning system, and energy storage system of capacitor banks forming DC link between choppers (DC-DC converters) and inverters (DC-AC converters), and batteries used for energy storage. The power electronics interface performs the duty of shaping and controlling voltage and frequency based on the purpose of different control strategies. The load for the stand-alone system can be of many types, both DC (television, lighting) and AC (electric motors, heaters, etc) [2]. The most frequently encountered elements of the power conditioning units are DC-DC converters and AC-DC inverters [3].

2. Components of the Proposed Model

A proposed architecture of a PV generation system used for feeding an AC load, using power electronics interface is illustrated in Figure 1.

The proposed PV generation system is composed of the following components:

1. *PV generator*: this is the whole assembly of solar cells, connections, protective parts, supports...etc. The focus is only on cell/module/array design and modeling.
2. *Step up DC-DC converter*: this power electronic system is used to adjust the output voltage to the required level of operation.
3. *Maximum power point tracking* algorithm: used to operate the solar array system at its maximum power for each level of radiation.
4. *DC link*: which is a capacitor bank used for energy storage and to maintain balance between the DC power and the AC power transferred to the load.
5. *DC-AC inverter*: used to supply the required three phase 50 Hz output voltage to the AC load, and it is controlled using pulse width modulation (PWM) techniques.
6. *LC Filter*: the filter is used to eliminate switching frequency harmonics.
7. *AC load*: it could be a heater, electric motors...etc.

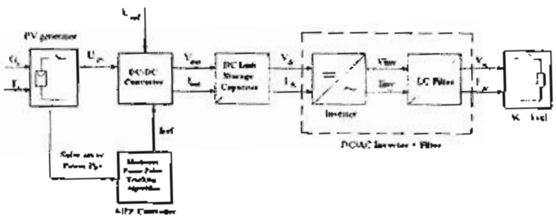

Figure 1. Proposed Architecture of a Direct Coupled PV -AC Generation System

2.1 PV Generator (Solar Cells)

The authors have proposed a detailed mathematical model for the PV generator in [4]. The proposed mathematical model based on four component-three parameters has been tested to simulate different types of photovoltaic panels constructed with different materials.

2.2. Step up DC-DC converter

The DC-DC converters are characterized generally by the following characteristics:

- Convert a fixed-voltage dc source into a variable-voltage dc source.
- DC chopper directly converts dc to dc.
- It can be used to step-down or step-up a dc voltage source (as compared to AC transformers with a continuously variable turn's ratio).

Two-quadrant choppers may be a part of autonomous power supply system that contain battery packs and such renewable dc sources photovoltaic arrays, fuel cells, or wind turbines [5]. The arrangement used for step-up operation is shown in Figure 2.

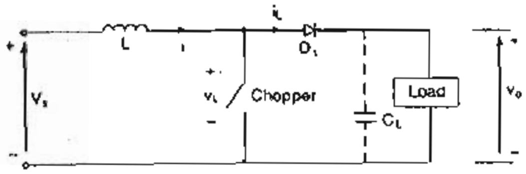

Figure 2 Step-up arrangement

2.3 Maximum Power Point Tracking Algorithm

The maximum power point tracker (MPPT) is now prevalent in grid-tied PV power systems and is becoming more popular in stand-alone systems. MPPT is a power electronic device interconnecting a PV power source and a load, maximizes the power output from a PV module or array with varying operating conditions, and therefore maximizes the system efficiency. MPPT is made up with a switch-mode DC-DC converter and a controller. For grid-tied systems, a switch-mode inverter sometimes fills the role of MPPT. Otherwise, it is combined with a DC-DC converter that performs the MPPT function [6]. The location of the MPP in the I–V plane is not known beforehand and always changes dynamically depending on irradiance and temperature. For example, Figure 3 shows a set of PV I–V curves under increasing irradiance at the constant temperature (25 °C). Therefore, the MPP needs to be located by tracking algorithm, which is the heart of MPPT controller.

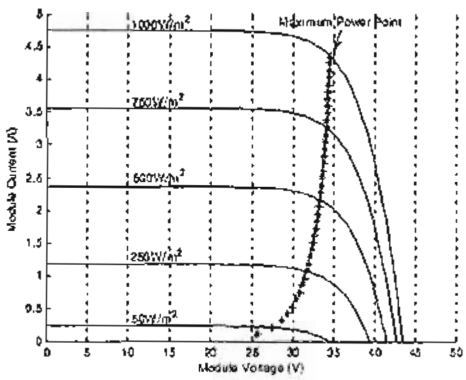

Figure 3 MPP for different irradiation levels

There are a number of methods that have been proposed. One method measures an open-circuit voltage (V_{oc}) of PV module every 30 seconds by disconnecting it from rest of the circuit for a short moment. Then, after re-connection, the module voltage is adjusted to 76% of measured Voc which corresponds to the voltage at the MPP [7]. The implementation of this open-loop control method is very simple and low-cost although the MPPT efficiencies are relatively low (between 73~91%) [8]. Model calculations can also predict the location of MPP; however in practice it does not work well because it does not take physical variations and aging of module and other effects such as shading into account. Furthermore, a pyranometer that measures irradiance is quite expensive. Search algorithm using a closed-loop control can achieve higher efficiencies, thus it is the customary choice for MPPT. Among different algorithms, the Perturb & Observe (P&O) is used for the proposed system design.

The perturb & observe (P&O) algorithm, also known as the "hill climbing" method, is very popular and the most commonly used in practice because of its simplicity in algorithm and the ease of implementation [8]. The most basic form of the P&O algorithm operates as follows. Figure 4 shows a PV module's output power curve as a function of voltage (P-V curve), at the constant irradiance and the constant module temperature, assuming the PV module is operating at a point which is away from the MPP.

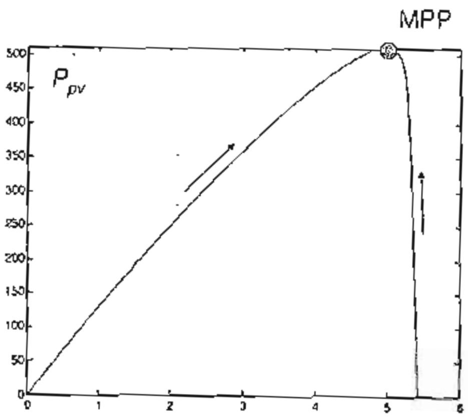

Figure 4: Plot of power vs. voltage for BP SX 150S PV module (1KW/m, 25° C)

In this algorithm the operating current of the PV module is proposed to be perturbed by a small increment, and the resulting change of power, P, is observed. If the P is positive, then it is supposed that it has moved the operating point closer to the MPP. Thus, further current perturbations in the same direction should move the operating point toward the MPP. If the P is negative, the operating point has moved away from the MPP, and the direction of perturbation should be reversed to move back toward the MPP. A simple "perturb and observe" MPP tracking algorithm is illustrated in Figure 5. The objective of the MPP tracking algorithm is to adjust the DC-DC control variable so that the PV array operates at the maximum power point, thus, in order to achieve the objective:

- It is assumed that the step up output voltage $V_{out} = V_{dc}$ is constant.
- I_{ref} is used as the control variable for the step up DC-DC converter.
- PV array current ideally tracks the step up input current reference: $I_{pv} = I_{ref}$.

A Matlab-Code is developed to be used in a function block during simulations.

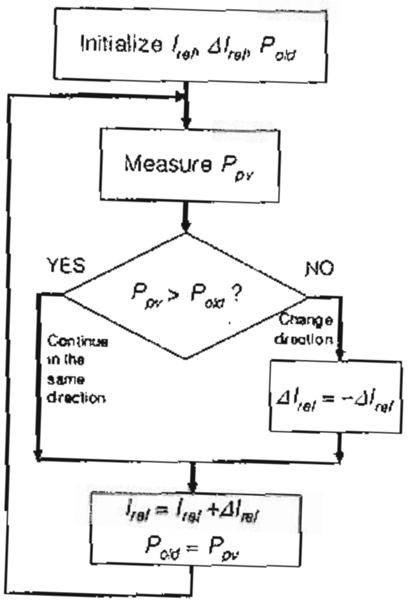

Figure 5 Flowchart of the P&O algorithm

2.4 The DC link

The DC link capacitor voltage is a measure for the balance between the flows through the electrical conversion processes from DC power supplied by the DC-DC Chopper to AC power supplied by the DC-AC inverter to the AC load [9]. Figure 6 shows the operation principle of the DC link storage capacitor. The dc capacitor is assumed to be large enough to sustain changes in dc current without changes in the dc voltage and basically, at steady state operation, can be considered as a dc voltage source [10].

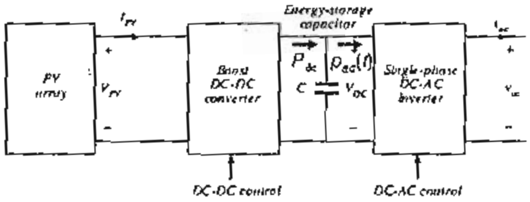

Figure 6 DC link energy storage capacitor

2.5 DC-AC Inverter

Inverters are widely used in industrial applications (e.g. variable speed dc motor drives, induction heating, standby power supplies, and uninterruptible power supplies (UPS)). The input may be a battery, fuel cell, solar cell, or other dc source. The widely used type of Inverters is the Pulse width modulated (PWM) Voltage Source Inverter (VSI) [3, 5]. The main advantage of PWM converters is the possibility of controlling the converter gain and consequently the converter output voltage. There are numerous PWM techniques used with different converter configurations. In the most popular PWM method, the width of each pulse is varied in proportion to the amplitude of a sine wave or so-called control waveform as seen in Figure 7.

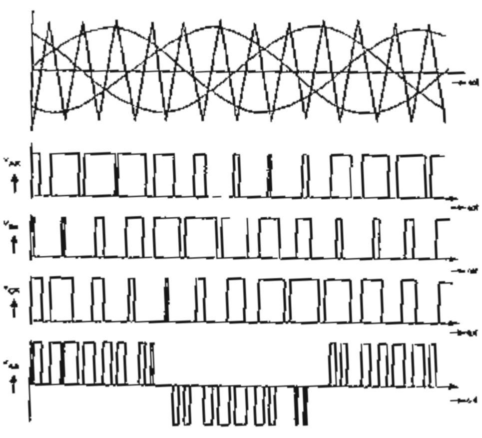

Figure 7 Three-phase sinusoidal PWM inverter waveforms

There phase VSI is shown in Figure 8 [10]. It is a two level bridge composed of six valves. Each valve is made of semiconductor turn-off capable switches and an anti-parallel diode. The switch should be designed only for forward blocking voltage, as diodes ensure that the voltage polarity of each switch is unidirectional. However, each converter arm, made of two valves, can conduct current in both directions, providing the converter with the capability to behave as an inverter or rectifier [10]. More detailed information is presented in [3, 5].

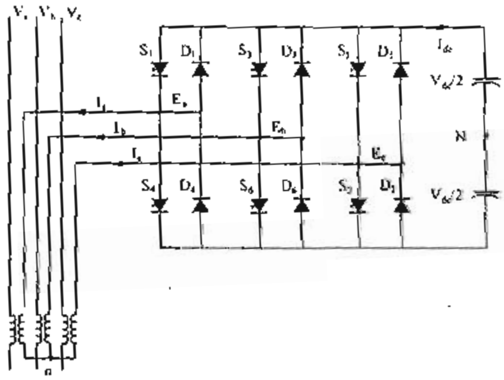

Figure 8 Three-phase sinusoidal PWM inverter structure

2.6 The LC Filter

An L-C Filter is chosen to remove the switching harmonics of the inverter output voltage; the objective is to obtain near pure sine wave of the load voltage and to decrease the total harmonic distortion.

2.7 The AC Load

The load existing in a PV stand-alone system can be of many types, both DC and AC. The proposed PV system contains an electrical heater as an AC load. The heater is actually a simple resistance controlled by a thermostat. Thus, the load can be modeled as:

$$I_{ac} = V_{ac} / R_h$$

Where I_{ac}, V_{ac}, are the AC current and voltage of the load, respectively, R_h is the resistance of the heater, which can be determined by the rated power and the rated voltage.

3. Design and Simulation

This part of the paper provides the design and simulations of a PV generation system with MPPT feeding an AC load. It discusses the Component selection for the DC-DC Cuk converter and the DC-AC inverter.

3.1 The DC-DC Cuk Converter Design

The inductor sizes are decided such that the change in inductor currents is no more than 5% of the average inductor current. The following equation gives the change in inductor current [11].

$$\Delta i_L = \frac{V_s \cdot D}{L \cdot f}$$

where: V_s is the input voltage, D is the duty cycle, and f is the switching frequency. The design criterion for capacitors is that the ripple voltage across them should be less than 5%. The DC-DC converter inductor is chosen to be 0.2 mH, and the capacitor is 10 μFarad.

3.2 DC-AC inverter

The selection of the inverter R-C parameters is based on the documentation of Matlab [12], where the snubber resistance R_s is set to ∞ (infinity), and the snubber capacitance C_s is set to 0 (zero) to eliminate the snubber from the model.

3.3 Filter Design for the DC-AC inverter

The LC type filter used for reducing the switching frequency harmonics of the VSI is a second-order passive filter, which contains two reactive components that are inductor and capacitor. The inductor blocks high frequencies and passes low frequencies, while the capacitor passes high frequencies but blocks low frequencies. The impedance of a capacitor is inversely proportional to frequency or increasing frequency leads to reducing impedance. For an inductor, its impedance is directly proportional to the frequency. Increasing frequency leads to increasing impedance [13]. A method used by the authors in [14] is applied to design the LC filter, and the values chosen are L= 2 mH, with three phase capacitor bank of 3 kVar at 380 Vrms.

3.4 Validation of the Proposed PV System Design

After the component selection, Matlab-Simulink simulations validate the design and choice of the MPPT algorithm. Simulations verify the functionality of PV generation system with a resistive AC load. Measurements are taken at each step of the system to test, verify and validate the design. A Matlab-Simulink model of the system is created and shown in Figure 9.

Six PV modules of 85 W each are connected in series, to obtain a total of 510 W in ideal operation under standard testing conditions. The system was built up according to the proposed architecture in Figure 1, and with the required design operation. Assuming full radiation of 1000 W/m^2, Figure 10 shows the Boost DC-DC duty cycle = 0.78, the efficiency of the DC-DC converter = 0.98, the output PV voltage is adjusted to = 115 V, the reference current = the PV current = 4 A, and the output power of the DC-DC converter is equal to = 430 W and that of the PV power = 453.5 W and the ideal power one of 510 W.

The DC-AC output voltage which shows a square wave as expected and the load line to line voltage of 380 Vrms are illustrated in Figure 11. It is clear that the total harmonic distortion is reduced, and a fine sine wave appears.

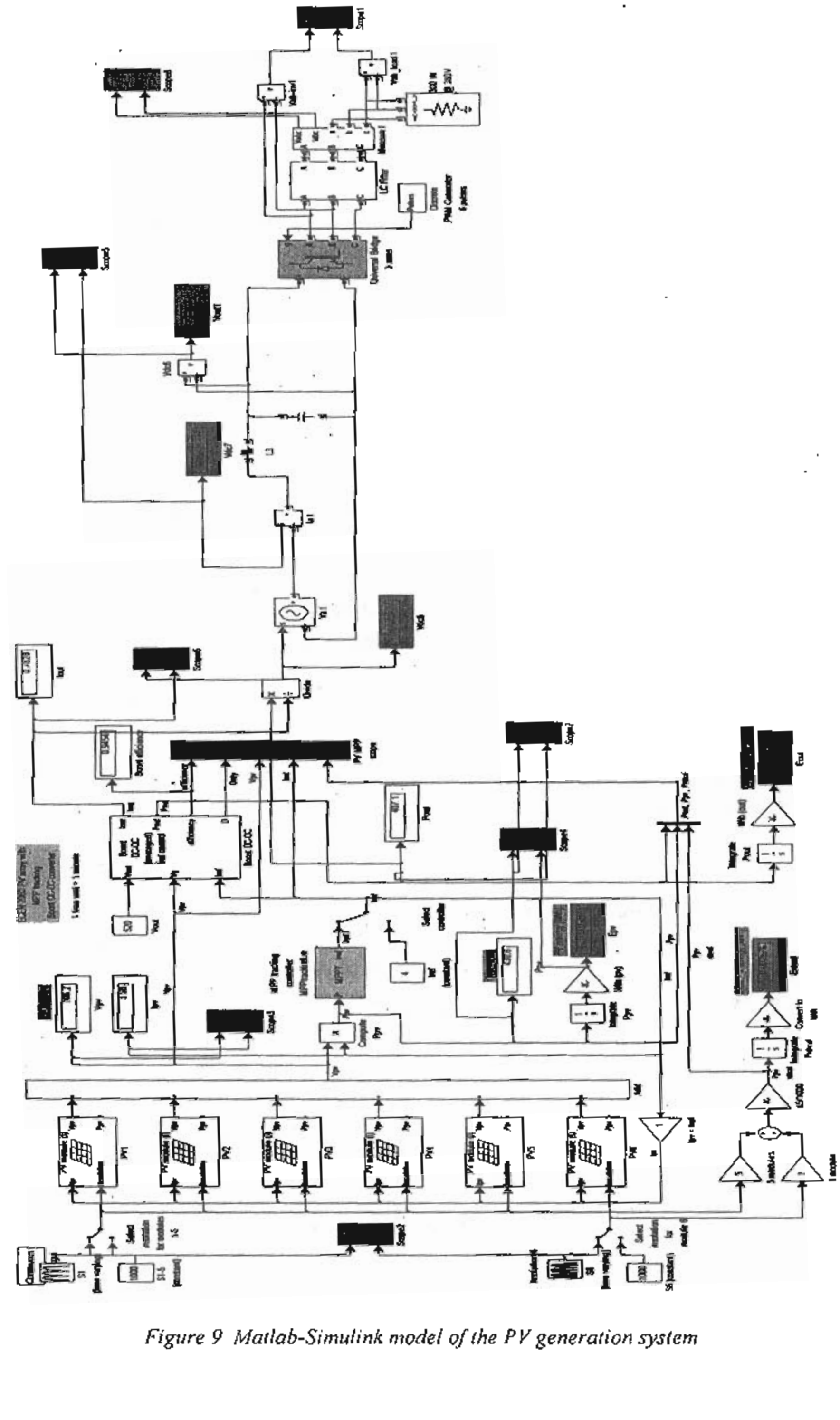

Figure 9 Matlab-Simulink model of the PV generation system

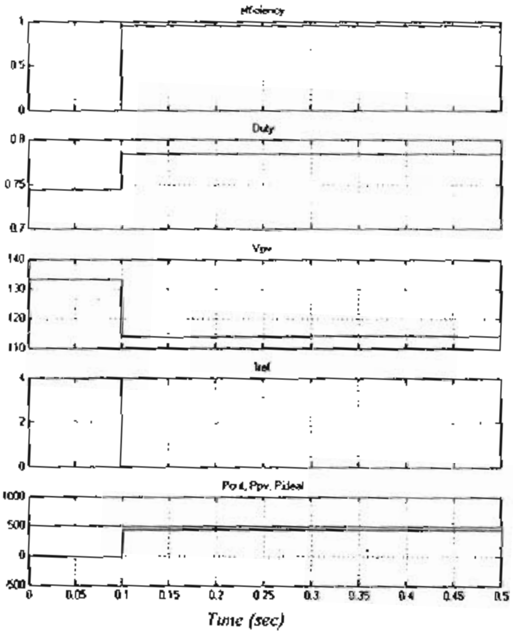

Figure 10 MPP measurements (1000W/m²).

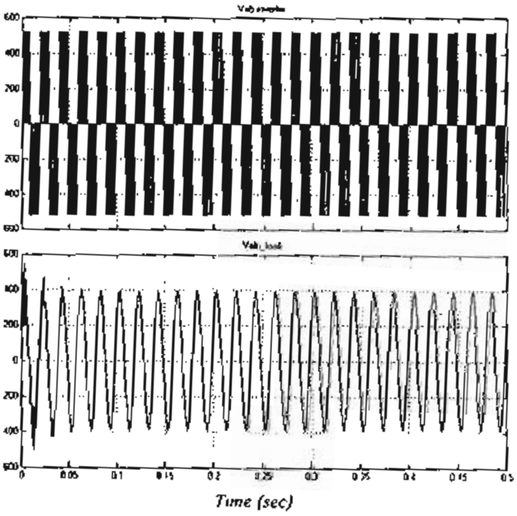

Figure 11. Inverter and load voltage measurements

The MPP tracking algorithm performs well under the test conditions, as well as the other system components, verifying the design and the operation of the PV generation system feeding an AC load. The MPP system always tracks the maximum power at each radiation level. The Simulink model is designed to read different operating conditions or radiation levels as illustrated in the following case. Figure 12 shows the proposed variation of the radiation levels for arrays from A1-A5 and for array A6.

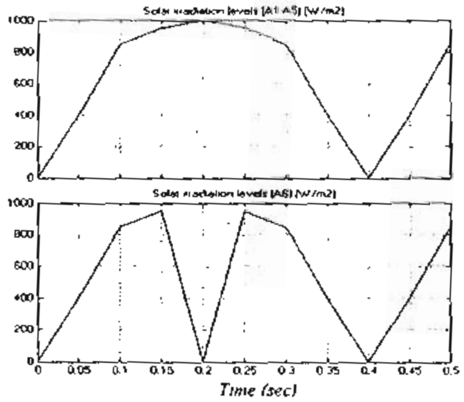

Figure 12 Variations of different radiation levels.

Figure 13 shows the variation of the PV system operating voltage with different radiation levels, while the MPP system keeps the current to the reference value, and keeps tracking the maximum power at each radiation level, as shown in Figure 14 of the PV array power and the DC-DC converter power.

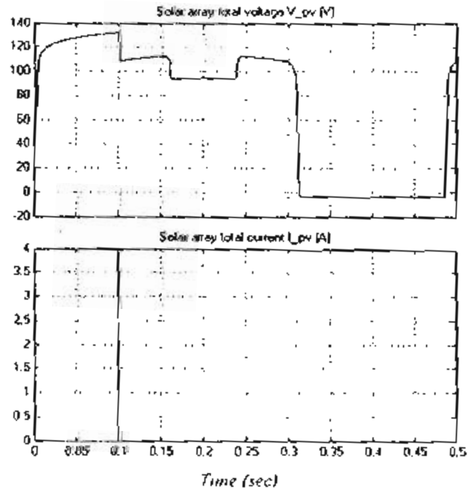

Figure 13 PV system output voltage and current.

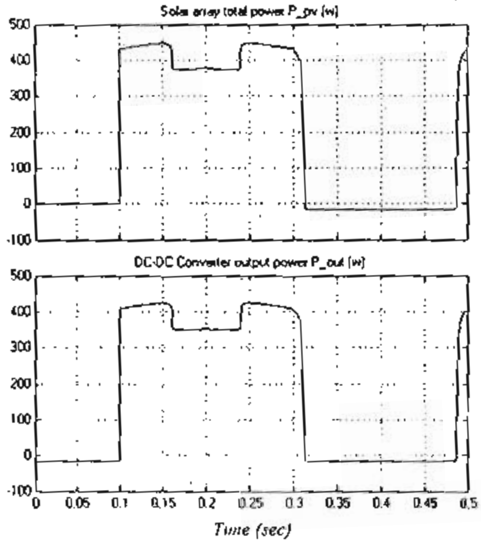

Figure 14 PV system output power and power of the DC-DC converter

The MPP measurements in this case are illustrated in Figure 15.

Figure 16 shows the stability of the DC link voltage, with variation of charging current, in order to maintain balance in the power transfer, as assumed in the design. The operation of the inverter is verified because of the stability of the dc link voltage providing power to the 300 W resistive AC load. Figure 17 shows the voltage of the inverter and the load.

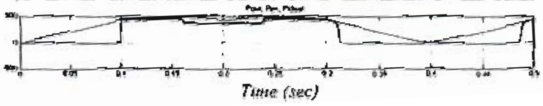

Figure 15 MPP measurements (variable radiation levels).

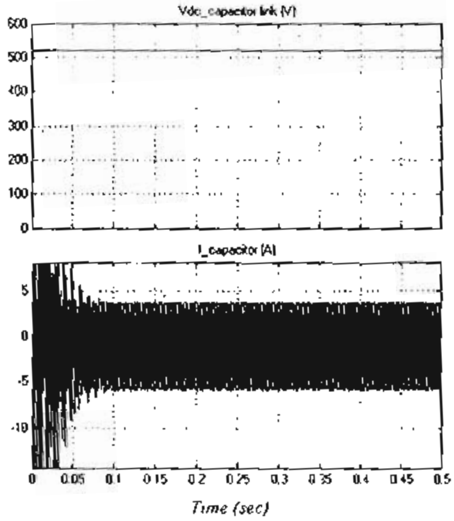

Figure 16 DC Link measurements (variable radiation levels).

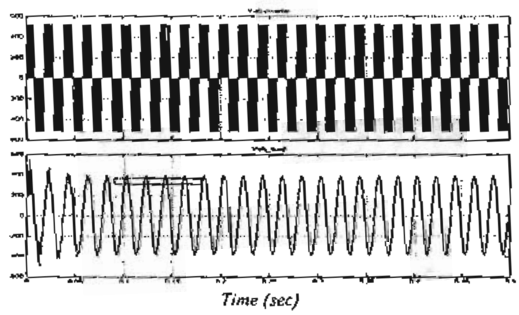

Figure 17 Inverter and load voltage measurements

4. Conclusion

Photovoltaic (PV) systems are ideally suited stand alone and distributed resource applications. PV systems produce DC electricity when sunlight shines on the PV array, without any emissions. The DC power is converted to AC power with an inverter that can be used to power AC loads.

This paper presents a proposed PVPS Simulink model suitable for direct coupled PV-AC load system. The model consists of PV generator, DC-DC converter, maximum power point controller, DC-AC inverter and energy storage system of capacitor banks forming DC link between DC-DC converters and DC-AC converters. The DC link is used also to maintain balance between the DC power and the AC power transferred to the load. The entire system components are designed and a Matlab-Simulink model is developed and simulated to validate the optimum design of them. Measurements are taken at each step of the system to test, verify and validate the design. An LC filter is designed and incorporated to the model to mitigate the harmonic produced by inverter.

A particular typical six PV modules of total power 510 W is used for model evaluation and results are compared with points taken directly from the manufacturer's published curves and show excellent correspondence to the model. Simulations verify the functionality of PV generation system with a resistive AC load.

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