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INTERCONNECTION OF A PHOTOVOLTAIC GENERATOR (PVG) TO A MAIN SUPPLY: A PRACTICAL STUDY

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Abstract. *This paper presents a technique for interconnecting a photovoltaic generator (PVG) to a main supply of AC nature. The technique has been implemented practically in one of the laboratories of the author's work place. The technique uses a single phase full wave bridge rectifier. Such bridge rectifier is operated in an inverter mode of operation and that is to guaranty its contribution of real power to a main AC supply. The bridge rectifier is controlled by a practical firing angle controller developed in LABVIEW software environment. The firing angle controller is interfaced to the power bridge rectifier through the use of simple optocoupler and pulse transformer elements. The practical results show that under a certain insolation/irradiation level (taken randomly) and for a resistive load requiring presumably130 W power , the PVG source was contributing 90 W power to such power load and the AC grid was contributing 40 W to such power load*

The technique of interconnection alleviates the problem of synchronization encountered often when using the traditional way of interconnecting the DC grid (made of conventional renewable energy resources) to the AC grid system.

Key words: Integration of Renewable Energy Sources to Grid Systems, Photovoltaic Generation System, AC/DC Converter Applications, LABVIEW Applications.

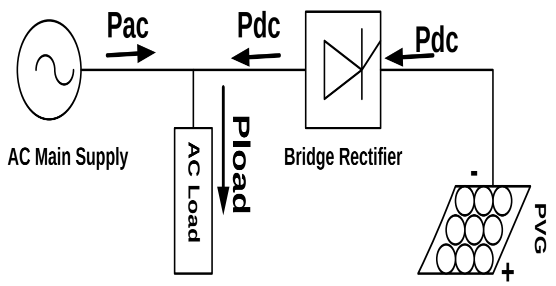
1. Introduction

With the increasing concerns about global warming issues, renewable energy resources turn to be gaining more energy demand applications. Unfortunately, most (if not all) renewable energy resources suffer currently from the lack of providing constant power when the surrounding weather and the environmental conditions change. Due to such non-constant power provision characteristic, storage batteries are traditionally employed in parallel with the renewable energy resources and that is to supply any deficiency or to absorb any excess in load energy requirements. Unfortunately, the storage batteries are characterized by an additional considerable cost to renewable energy resources cost. Moreover, the storage batteries have also a short life time when compared to the life time of the renewable energy resources. A wise solution to overcome the problem of relying totally on the power generated only by the renewable energy resources is to constitute a hybrid DC grid that should contain or connect all conventional renewable energy resources plus storage units (storage batteries + fly wheels) in parallel and interconnecting such hybrid DC grid to the AC grid using power inverter [1-3] modules. It is meant by conventional renewable energy resources: PVG panels, wind farms, and fuel cells units. A glance at the anticipated task from such proposed solution is that at any time of operation and for any prospective energy load demand the energy is guarantied from the DC grid as well as from the AC grid. One should note that it will be nice to use the AC grid whenever there is deficiency in energy from the hybrid DC grid. The ultimate goal of the proposed solution is to ease the constraint on relying totally on the storage batteries.

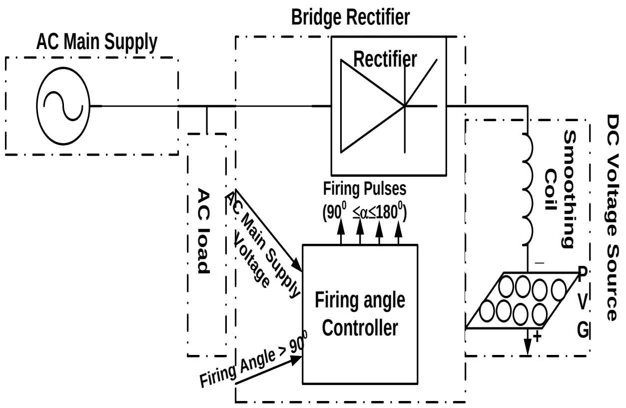
This paper proposes an idea of interconnecting a photovoltaic generator (PVG) to a main AC supply. The idea consists of using a full wave rectifier as an interface module between the AC and the DC supplies sides. In the AC side, a main supply and a load are found while in the DC side, a PVG source in series with a reactor are allocated. The condition that needs to be imposed on the interface bridge rectifier is to use it in a inverter mode of operation [4]. This condition is needed for the sake of providing a negative value for the average voltage at the DC side. The negative value of the average voltage is guarantied by a firing angle having values greater than 90^0 following the zero crossing of the AC load voltage. The negative value of the average voltage at the DC times the PVG positive source current results in a negative value of the power at the DC side of the bridge. A negative value for the power means that the DC power from the PVG is pumped to the AC side/grid. The proposed idea has been built and tested in one of the laboratories of author's workplace (i.e University of Bahrain). The idea used LABVIEW software [6] as a practical firing angle controller. The practical results prove the feasibility and effectiveness of the proposed idea under a number of insolation/irradiation levels

2- Study System

A general scheme of the study system is represented in figure 1. The desired powers flow is simplified in figure 1(a). Figure 1(b) consists of four main parts: An AC 50 Hz voltage source, an AC load, a bridge rectifier controlled by a firing angle controller, a DC voltage source consisting of a PVG source in series with a reactor. The polarity of the PVG is reversed in the figure and that is to indicate that the PVG will be generating power rather than absorbing power. The bridge rectifier is controlled by a firing angle controller. The next subsections describe the PVG model and the contents of the important blocks of figure 1.



(a)



(b)

Figure 1: Study System

2.1 Photovoltaic Generator (PVG): Model and Characteristics

The photovoltaic generator (PVG) is an array of solar cells combined in series and parallel to provide PV panels. Figure 2(a) shows a photo of five PV panels that were used in this investigation. Any possible series and parallel combination of the PV panels will make a voltage source termed from now on in this paper PVG source. The mathematical model of a PV panel is extracted from reference [5]. Such model is known as Akbaba's model and it is reproduced here in the form of:

$$I_g = \frac{(Voc - V_g)}{A + BV_g^{\,2} - CV_g} \qquad (1)$$

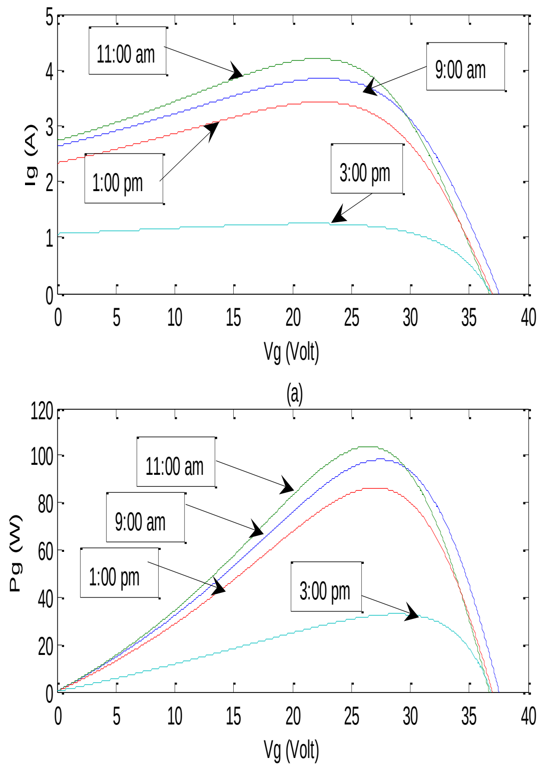
Voc (open circuit voltage), **A, B**, and **C** are parameters that depend on the insolation/irradiation level.
Vg is the voltage across the PV panel terminals
Ig is the current delivered by the PV panel when an external load is connected across its terminals.

Appendix A.1 describes the procedure and results of estimating the online values of the parameters **Voc, A, B,** and **C** for the PV panels used in this investigation.

Based on such results, the *I-V* and *P-V* characteristics of the PV panel were obtained. Figures 2(b) and 2(c) visualizes such characteristics at 9:00 am, 11:00 am, 1:00 pm, and 3:00 pm of the day of 27th October 2009. It should be noted that that the PV characteristics are obtained simply from the calculation:

$$P_g = V_g I_g = \frac{V_g(Voc - V_g)}{A + BV_g^{\,2} - CV_g} \qquad (2)$$

(a)



(c)

Figure 2: a) Photo of Considered PV Panels b) I-V Characteristics b) P-V Characteristics

In this investigation, two PV panels were connected in series to establish the PVG source of figure 1. One might wonder why not all four PV panels had been used, the answer to such worry can be justified by the limitation of the ratings of the power apparatuses used in conjunction with the PVG source.

2-2 Bridge Rectifier:

The bridge rectifier is no more than four power thyristors connected as shown in figure 3. The rectifier should operate in an inverter mode of operation. This means that the firing angle provided to the valves of the bridge should be greater than 90^0. Understanding and analyzing a bridge rectifier working under an inverter mode of operation is well documented in chapter 6 of reference [4] and more importantly one can easily note that the average value of the voltage at the dc side obeys the following expression [4]:

$$V_{DC} = K_1 \cos(\alpha) \qquad (3)$$

In which

K_1 : is a positive constant that depends on the rms value of the main supply voltage

α : is the firing angle

It is clear that for any value of the firing angle greater than 90^0, the average voltage V_{DC} is negative.

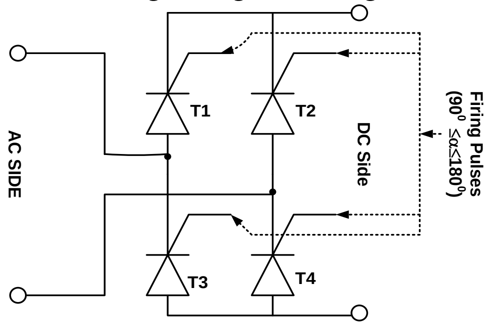


Figure 3: Single Phase Full wave Bridge Rectifier working in an inverter Mode of Operation

2-3 Firing Angle Controller:

The proposed firing angle controller is shown in the general block diagram of figure 4. Understanding the operation and desired signal from each block of such figure can be refereed to the examination of the output signals of figure 5. Such figure 5 is self explanatory.

It is worth to state that:

- The proposed firing controller needs two inputs: the main supply voltage waveform and the manual entry of the firing angle value.
- The proposed firing angle generates two outputs: train of pulses that are synchronized with the desired firing angle ($\alpha \geq 90^0$).
- The proposed controller detects the zero crossing of the main supply voltage automatically.

Figure 7 shows a LABVIEW file of the proposed firing angle controller. Such LABVIEW file was used in the performance prediction of the study system in this paper.

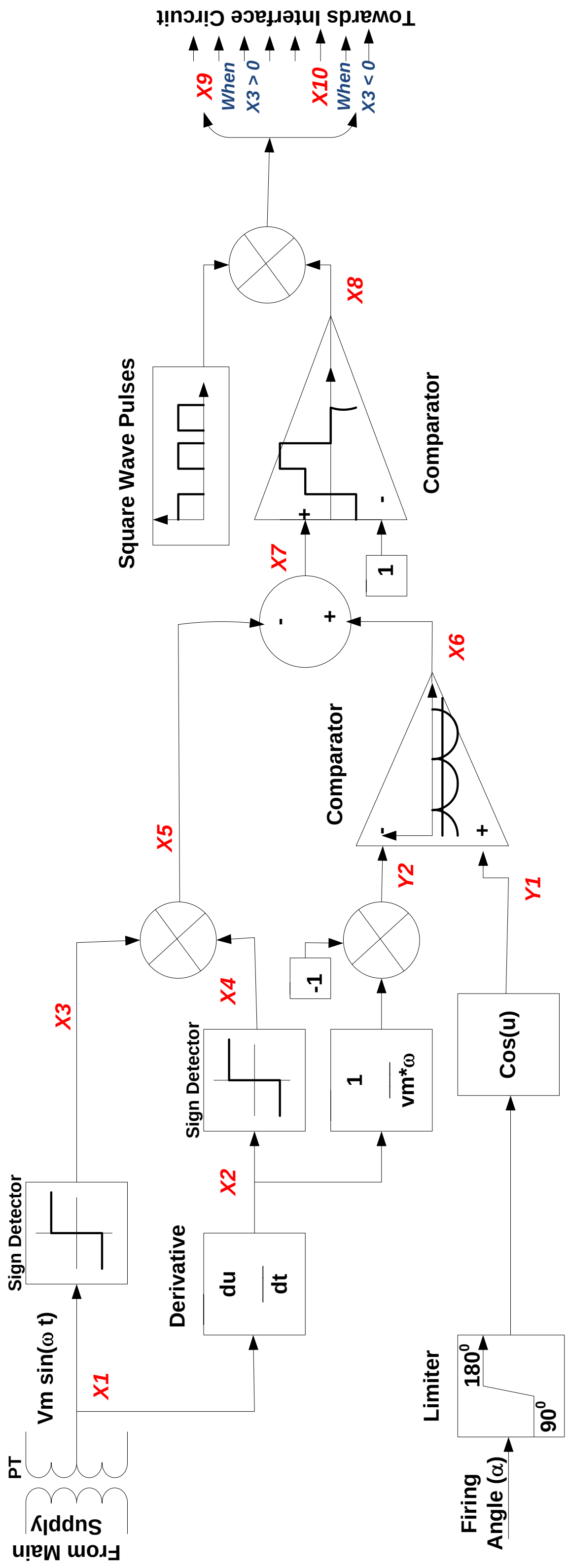


Figure 4: General Block Diagram of the Firing Angle Controller

Interfacing the proposed firing angle controller from the power circuit has been done practically by using two configurations similar to the circuit of figure 6. It should be noted the output signal (X9) of figure 4 is supplied to the input signal (X9) of figure 6 through a data acquisition card (DAQ). Such card carries the code PCI6221 and it is designed by National Instruments Incorporation.

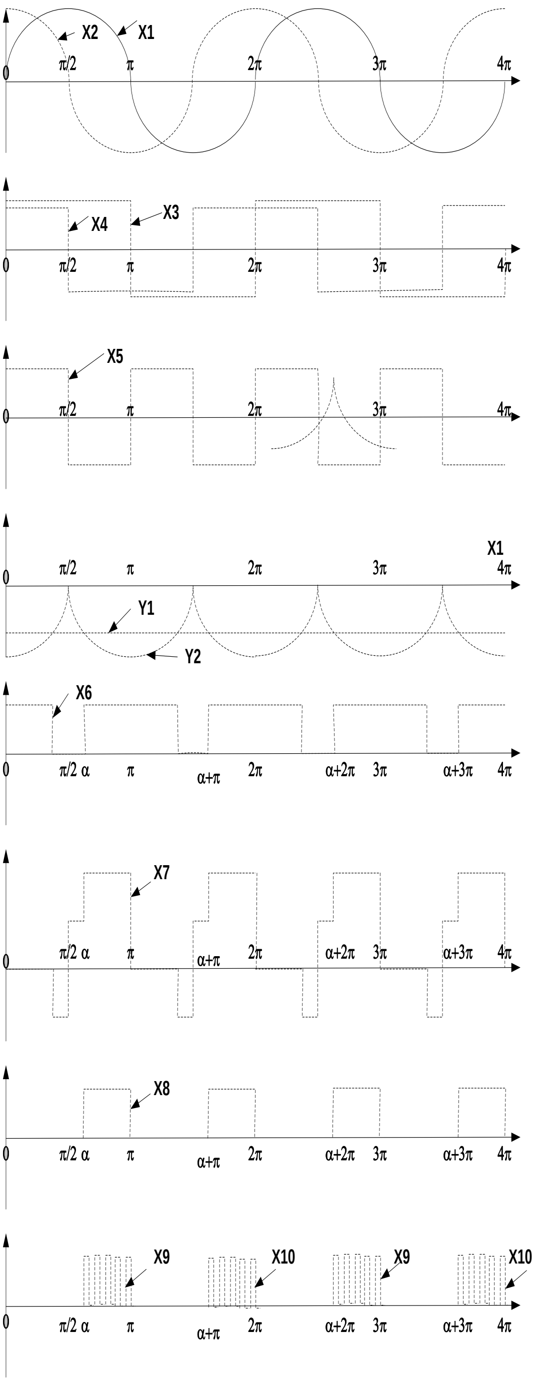


Figure 5: Anticipated Waveforms at Different Blocks of The Firing Angle Controller

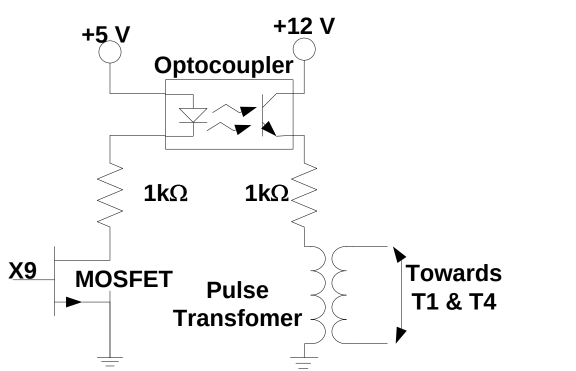


Figure 6: Interface Circuitry Between Labview and Power Circuit.

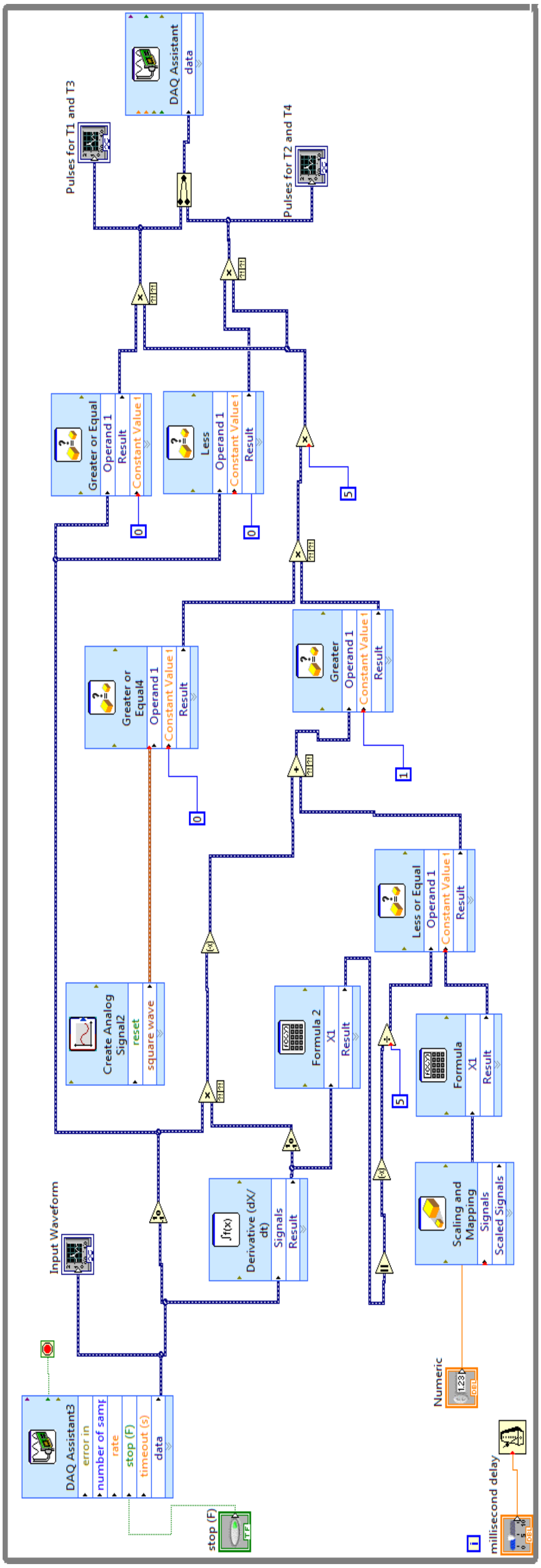


Figure 7: LABVIEW File of the Firing Angle Controller.

3- System Performance

The performance of the proposed interconnection was evaluated practically. Figure 9 shows a photo of the studied power circuit.

Figure 9: Photo of The Studied System

The circuit connection of such photo is shown in figure 10. The system parameters data are provided in Table 1.

Table 1: Parameters Values

Vs (V)	AC load (Ω)	Smoothing Reactor (H)	Controlled Resistance (Ω)	PVG
90	60	0.45	60	Series of 2 PV panels whose characteristics are shown in figure 2.

The performance looked for consisted of measuring the power consumed by the AC load (**Pac**), power delivered by the AC source (**Ps**), and power delivered by the PVG source (**Ppvg**). The measurements were held on the date of Saturday December 5^{th}, 2009 and repeated several times during that day. It should be mentionned that at each time of the measurements:

- the firing angle value was entered manualy180^0 (in the front panel of LABVIEW software) then decreased (also manualy) until a máximum value of the PVG power (Ppvg) was observed.
- The controlled resistance in figure 10 was set to its máximum value at the beginning of each measurement then was gradually decreased until being shorted-**out**. The reason for such maneuver was to avoid any quick tendance to the short circuit conditions of the PVG source.

Figure 11 shows snapshots of the watmeters readings before the interconnection of the PVG (figure 11(a)) and after the interconnection of the PVG (figure 11(b)). Such readings were taken at 9:45 am.

As can be seen:

- Before the interconnection of the PVG (i.e when the gates of the thyristors of the bridge rectifier were not fired), the main AC supply power and the power absorbed by the AC load were equal to 130 W. The PVG power was zero. This means that the AC load was relying totally on the main AC supply.
- After firing the gates of thyristors, the AC power load is still 130 W but the main AC supply power dropped to 40 W. This means that the main AC supply was contributing 30.77 % (i.e 40/130*100) of power required by the AC load. Naturally, the remaining 69.23 % power was supplied by the PVG source.

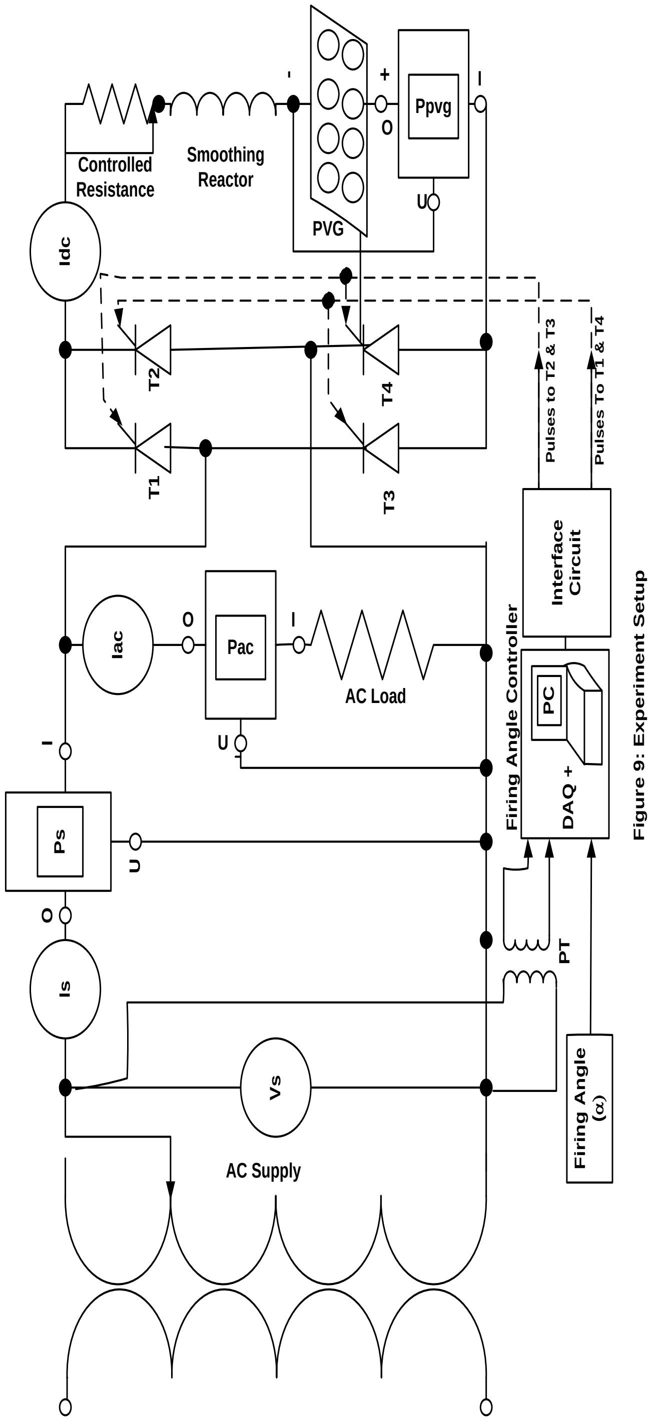
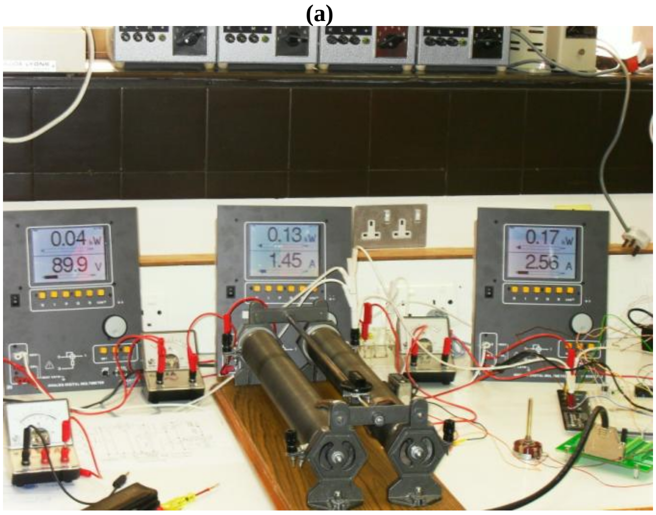


Figure 10: Experiment Setup

(a)



(b)

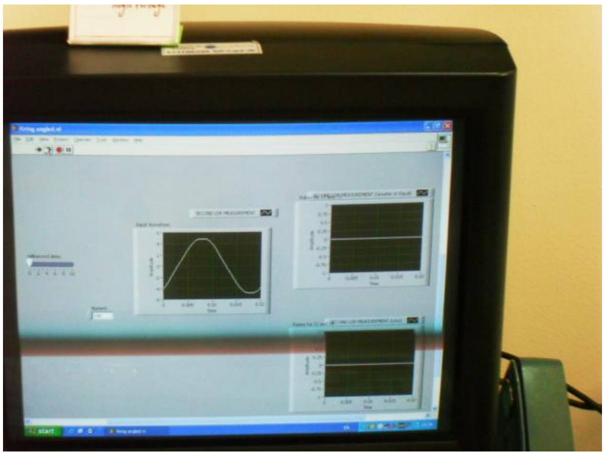
Figure 10: Power Measurements (From left to Right: Main Supply Power (**Ps**), AC load Power **(Pac**), PVG source Power (**Ppvg**)) a) Before the interconnection of PVG source. b) After the interconnection of PVG source.

Figure 11 visualizes LABVIEW snapshots of the supply voltage waveforms, firing pulses to thyristors T1& T4 and firing pulses to thyristors T2 & T3

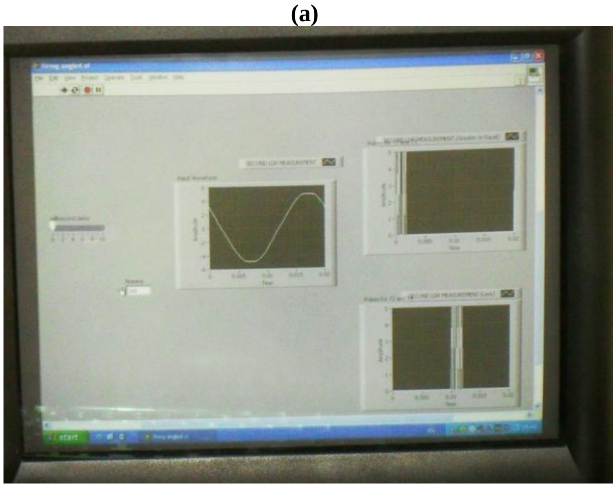
4. Conclusion

Interconnecting PVG source to a main AC supply was investigated practically in this paper. The interconnection was done using a bridge rectifier. The bridge rectifier was operated in an “inverter mode of operation”. The bridge rectifier was controlled by a developed LABVIEW file.

Quite encouraging results were reached when taken under a random irradiation level. For an almost 130 W power required by an ac load connected at the ac side of the bridge, the PVG source contributed nearly 69.23 % of such power while the main ac supply supplied the rest 33.77 % of power to the AC load. The reader might question 130W is not a big value to talk about. The answer to such inquiry persists in taking necessary lab safety precautions and in limiting the ratings of the used apparatuses.



(a)



(b)

Figure 11: Snap Shot of the System Performance a) Supply Voltage & Firing Pulses to Thyristors.) Before the interconnection of PVG source. b) After the interconnection of PVG source.

The good characteristic of the proposed idea of interconnection is that no worries are encountered when synchronizing the DC system with the AC system (frequency and phase angle are not altered).

As to the limitations of the work done in this investigation, one can state the following points which might be considered as recommendations for future elaborations in the subject:

- To establish a closed control loop that will be able to adjust the value of the firing angle automatically when extracting the maximum power point from the PVG source when the level of surrounding insolation/irradiation change.
- Quality of the voltages and currents signals generated by the rectifier and necessary active power filter should be installed in proper allocations.

References

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[6] LABVIEW Software. Version 8.6, National Instruments Inc., Texas, 2007.

Appendix

Determination of PVG Parameters

The values of the parameters **Voc**, **A, B,** and **C** of the PV panels considered in this investigation are tabulated thorough the conduction of simple laboratory tests. That was done thorough the measurements of the voltage and current of the four PVs panels as illustrated in figure A.1. The measurements were carried out online from 8:00 am to 4:00 pm in the day of 27th October 2009.

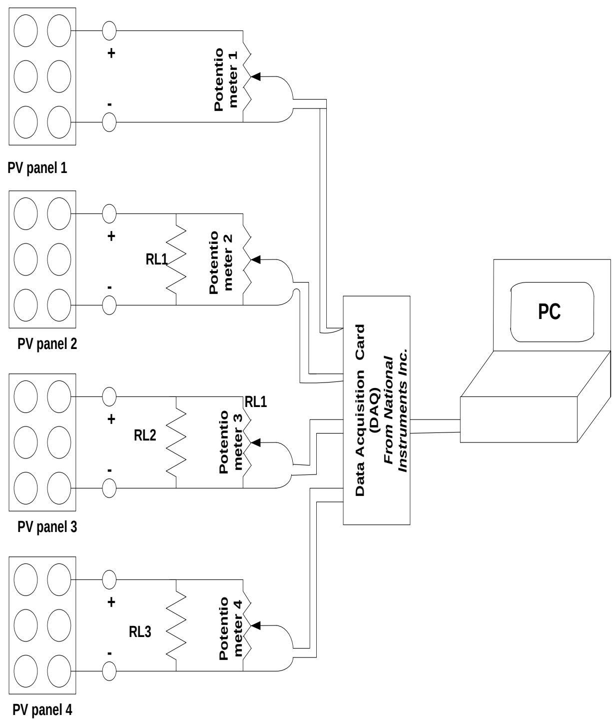

Figure A.1: PVG Parameters Estimation: Circuit Setup.

At each measurement, PV panels voltages (let them to be Vm1, Vm2, Vm3, Vm4) are recorded and consequently four currents are tabulated as Im1=0, Im2=Vm2/RL1, Im3=Vm3/RL2, and Im4=Vm4/RL3. Having four voltages and four currents, the following system of four nonlinear equations was solved iteratively to find the parameters **Voc**, **A, B,** and **C**.

$$I_{m1} = \frac{(Voc - V_{m1})}{A + BV_{m1}{}^{2} - CV_{m1}} \qquad (A.1)$$

$$I_{m2} = \frac{(Voc - V_{m2})}{A + BV_{m2}{}^{2} - CV_{m2}} \qquad (A.2)$$

$$I_{m3} = \frac{(Voc - V_{m3})}{A + BV_{m3}{}^{2} - CV_{m3}} \qquad (A.3)$$

$$I_{m4} = \frac{(Voc - V_{m4})}{A + BV_{m4}{}^{2} - CV_{m4}} \qquad (A.4)$$

The behaviors of such parameters are visualized in figure A.2

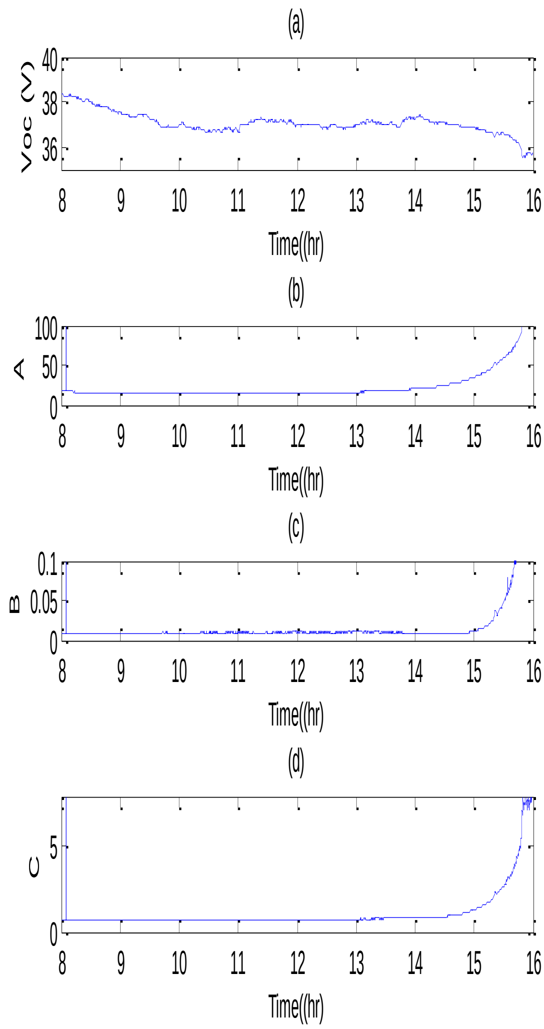

Figure A.2: PVG Parameters Values a) Open Circuit Voltage Voc b) Parameter A
c) Parameter B, d) Parameter