

INTERCONNECTION OF A PHOTOVOLTAIC GENERATOR (PVG) TO A MAIN SUPPLY: A SIMULATION 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 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 also operated in such a way that its control circuit (i.e triggering circuit) is self adjusted when extracting the maximum power from the PVG and injecting such power into to the main AC supply. The proposed technique has been formulated by a MATLAB/SIMULINK model. The simulation of the developed simulink model shows for a certain pre-defined AC load that up to 66.39 % of the power required by an AC load is obtained from the PVG source. The remaining 33.61 % of power required by the AC load is provided by the main AC supply. The Simulink model shows also that nearly 99.14 % of power can be extracted from the PVG source at a certain pretended solar radiation level (i.e insolation level).*

Key words: Integration of Renewable Energy Sources to Grid Systems, Photovoltaic Generation System, Maximum Power Point Tracker, AC/DC Converter Applications, MATLAB/SIMULINK Applications.

1. Introduction

It is well known that most (if not all) renewable energy resources suffer from the lack of providing constant power when the surrounding weather and 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 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] modules. 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 guaranteed 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. The realization of the objective of the above proposed solution necessitates the development of advanced and smart power flow controllers. Such controllers may turn-out to be expensive and may not be flexible to certain modes of operation.

This paper continues the exploration of the author's idea reported in reference [2] which proposed a practical alternative to interconnect a PVG source to a main AC supply. Unfortunately, the author [2] had tried his work at a relatively low power ratings and more importantly he had not targeted the maximum extraction of power from the PVG source. That was due to the fact that he has operated his experimental setup on an open loop control way. This present contribution introduces a self-adjusted firing angle controller that can be attributed the term: maximum power point tracker and which is operated in closed loop format while targeting the maximum extraction of power the PVG source.

The work is done in the Matlab/Simulink environment and the simulation results prove the effectiveness of the tracker under a number of pretended insolation 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 voltage source representing a 50 Hz main supply in series with a pretended equivalent source inductance, an AC load requiring a constant power and it is connected at a point referred to usually in the literature by the term: point of common coupling (PCC), a bridge rectifier in series with a reactance representing the inductance of a power transformer, and 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.

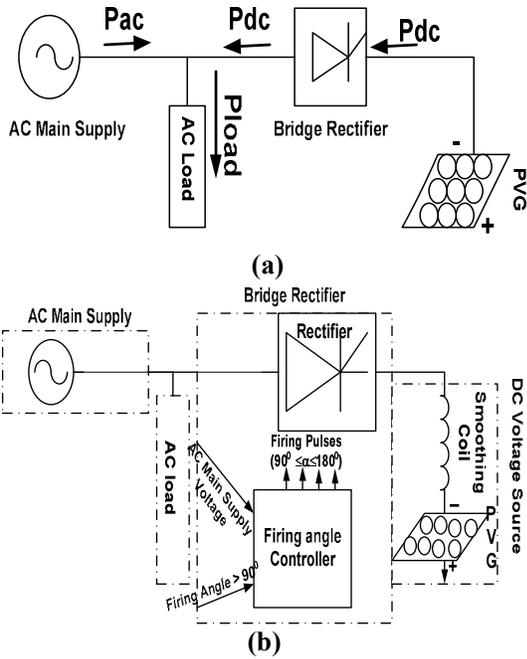


Figure 1: Study System

2-1 Photovoltaic Generator (PVG) Model

The photovoltaic generator (PVG) is an array of solar cells combined in series and parallel to provide a certain level of voltage and current. The voltage and current values are dependent on the prospective element that will be connected across the PVG external terminals. The PVG model does not differ in origin from the solar cell model. As to the solar cell model, it can be found in any physics or microelectronics textbook dealing with semiconductor devices. In this investigation, the PVG model is taken from reference [3]. Such PVG model is reproduced in the form of:

$$V_g = -0.9I_g + \frac{1}{0.0422} \ln\left(1 + \frac{I_{ph} - I_g}{0.0081}\right) \quad (1)$$

where

I_{ph} : photocurrent that is proportional to the insolation level

I_g : PVG supplied current

V_g : PVG source voltage

Such PVG model has been converted to another model called Akbaba Model [4]. Akbaba Model of the PVG generator is of the form:

$$I_g = \frac{(V_{oc} - V_g)}{A + BV_g^2 - CV_g} \quad (2)$$

where

V_{oc} : open circuit voltage across the terminals of the PVG generator at an insolation level

A, B, C : are parameters whose values depend on the insolation level. Such values can be easily tabulated by performing simple laboratory tests. The values of V_{oc}, A, B, C as well as the photocurrent I_{ph} of the used PVG in this investigation are provided in Table A-1 of the

Appendix. The way of tabulating such parameters is documented in the text of reference [4].

Akbaba PVG model of equation (2) is extended here to represent the PVG by a voltage source model rather than a current source model. Such voltage source model is of the form:

$$V_g = \frac{(CI_g - 1) + \sqrt{(1 - CI_g)^2 + 4BI_g(V_{oc} - AI_g)}}{2BI_g} \quad (3)$$

The I_g - V_g characteristics of the PVG source at different sun insolation levels (100 %, 90 %, 80 %, 70 %, 60 % levels from top to bottom) are depicted in figure 2 (a). For a specified insolation level, the voltage V_g times the current I_g determines the power that can be generated from the PVG source.

$$P_g = V_g I_g = \frac{V_g (V_{oc} - V_g)}{A + BV_g^2 - CV_g} \quad (4)$$

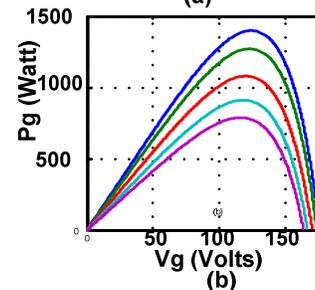
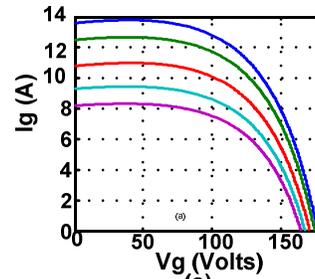


Figure 2: PVG Characteristics a) I-V Characteristics b) P-V characteristics

This calculations of such power are depicted in figure 2 (b) for different insolation levels (i.e 100 %, 90 %, 80 %, 70 %, 60 % levels from top to bottom).

As it is seen in figure 2(b) the power curves exhibit maximums at certain voltage V_g . The maximum power points are desired to be reached in this investigation and that will constitute one of main duties or targets of the firing angle controller module of figure 1.

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 [5]. This means that the firing angle provided to the valves of the bridge should be greater than 90° . Understanding and analyzing a bridge rectifier working under an inverter mode of operation is well documented in chapter 6 of reference [5] and more importantly one can easily note

that the average value of the voltage at the dc side obeys the following expression [5]:

$$V_{DC} = K_1 \cos(\alpha) - K_2 L_S \quad (5)$$

In which

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

α : is the firing angle

K_2 : is a positive constant that depends also on the value of the frequency of the main supply voltage .

L_S : is the total value of the source and the transformer inductances that will create the commutation phenomenon in bridge rectifiers.

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

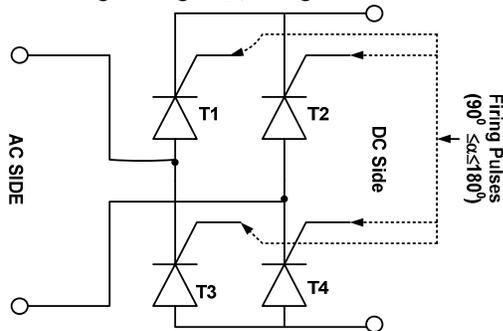


Figure 3: Single Phase Full wave Bridge Rectifier working in an inverter Mode of Operation

2-3 Firing Angle Controller:

The proposed firing angle controller of the bridge rectifier of figure 3 is shown in figure 4. Figure 4(a) is made of two blocks. The first block of figure 4(a) serves at finding and adjusting the on-line firing angle that guaranties a maximum extraction of power from the PVG source for a pre-set insolation level while the second block of the same figure (figure 4(a)) generates pulses that start at the firing angle (such angle is estimated by the first block and it should be greater than 90°) and end up at the next zero crossing of the PCC voltage waveform. Contents of the two blocks of figure 4(a) are further detailed in figure 4(b) and 4(c) respectively.

To explain how the firing angle control block diagram performs its job, pretend the system is initially working under certain steady state conditions. That is the firing angle corresponding to a certain desired PVG power ($P_{g,max}$) value is pre-determined. The desired PVG power ($P_{g,max}$) is the value of the maximum power that can be extracted from the PVG source at a certain insolation level. The relation between the insolation level and the maximum PVG power ($P_{g,max}$) is the contents of left upper block of figure 4(b). The analysis that is behind the development of such relation is detailed in part A.2 of the appendix in this paper. Actually, the maximum power ($P_{g,max}$) at a specified insolation level is more than finding the maximum of equation (4).

Now let us say there is a change in the insolation level. Such change indicates that there is a need to update the desired PVG power ($P_{g,max}$). By taking the absolute value of the probed power (P_D) at the DC side of figure 1 and subtracting from a new desired PVG power ($P_{g,max}$), an

error is tabulated. The absolute value of the error is checked whether it is between certain pre-set limits or not. In the case of having an error beyond the pre-set limits (and this is an often case encountered or expected when starting any initial simulation), a product of a non-zero value with the sign of the tabulated error is integrated and amplified. The output of the integrator is bounded between 90° and 180° . This is possible through the use of the limiter block that can be either allocated in the integrator block or cascaded with the integrator of figure 4(b). The firing angle (i.e output of figure 4(b)) is converted to a certain voltage level by the upper left block of figure 4(c). The voltage level is compared with the level of a saw tooth signal. The frequency of the saw tooth signal is 100 HZ and it is synchronized with the PCC voltage waveform.

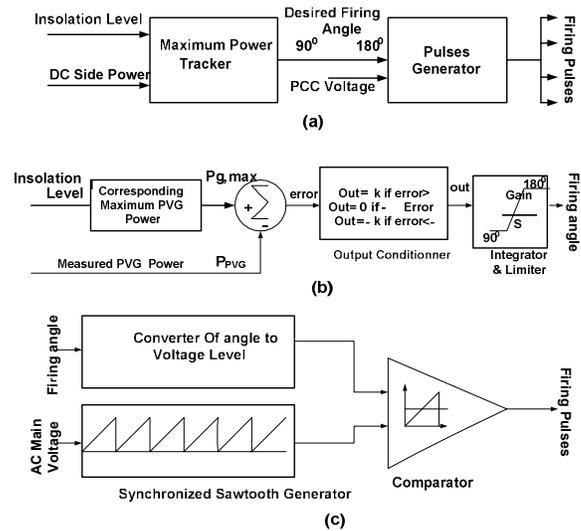


Figure 4: Firing Angle Controller a) General Block Diagram b) Maximum Power Point Tracker c) Firing Pulses Generator

Whenever the voltage level exceeds the saw tooth signal, there will be a generation of a pulse at the output of the comparator block diagram of figure 4(c). This pulse is fed to the gates of the SCRs of the bridge rectifier of figure 1. The previous process is repeated dynamically until the error of figure 4(b) decreases and tends to be zero or is within certain tolerance limits. This means that the firing angle value keeps changing automatically as the insolation level changes.

In summary, the firing angle controller should perform two tasks consequently:

- i. generate firing pulses to the thyristors of the bridge rectifier between 90° and 180° and that after detecting the zero crossing of the PCC voltage waveform
- ii. generated pulses at instants that correspond to the extraction of maximum power from the PVG source.

3- System Performance

The performance of the proposed technique of figure 1 has been evaluated or simulated using MATLAB/SIMULINK [6]. Figure A.1 of the appendix is the developed model for the system under study. The system data used in the simulations is provided in the appendix (Tables A-1 and A.2). The performance looked

for, when running the SIMULINK block of figure A.1, consists of measuring the power consumed by the AC load, power delivered by the AC source and power delivered by the PVG source. Such performance is dynamically tabulated for different pretended insolation levels. Figure 5 visualizes such performance for 5 different levels of insolation.

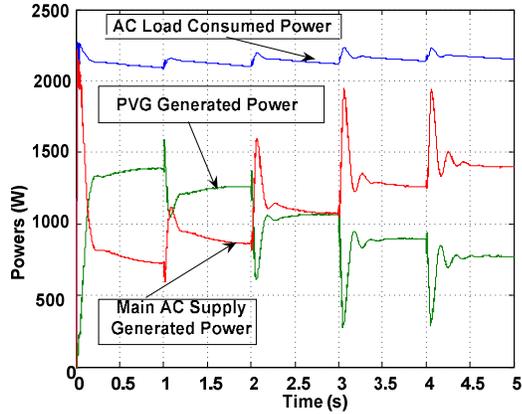


Figure 5: System Performance: Power Generation by PVG and AC Sources, and Consumption by AC Load

One remark that should be raised at this stage (before it may cause an ambiguity to the reader) is that the time coordinate in the X-axis in figure 5 is not a true time of day. It is simply a representation of a particular insolation level. The following table (Table 1) clarifies such ambiguity.

Time Period	Corresponding insolation level	Time Period	Corresponding insolation level
0 - 1	100%	3 - 4	70%
1 - 2	90%	4 - 5	60%
2 - 3	80%		

A close examination of the obtained curves at steady state conditions one can deduce that table 2 presents values or pictures of the power consumed by the AC load, power generated by the PVG sources and the main AC supply for five different insolation levels. The contributions of each generated source to the AC load are also calculated and the results of such calculations are shown in the last two columns of Table 2. A glance at the tabulated contributions, one can deduce that nearly 66.39 % of the AC load power is obtained from the PVG source.

When comparing the two curves for every pretended insolation level, one can conclude that nearly all possible generated power by PVG source is extracted at each presumable insolation level. Table 3 indicates the matching factor between the PVG generated powers and the PVG maximum power when steady state conditions are reached from the simulation process.

Insolation Level (%)	AC Load Consumed Power (W)	PVG Source Generated Power (W)	Main Supply Generated Power (W)	Contribution of PVG Source to AC Load (%)	Contribution of Main AC Supply to AC Load (%)
100	2090.	1388.	702.	66.39	33.61
90	2101.	1259.	841.	59.93	40.07
80	2118	1060.	1057.	50.09	49.91
70	2138	892.	1246.	41.71	58.29
60	2152.	767.	1384.	35.67	64.33

As to the question of how much power can be extracted from the PVG source for different insolation levels, figure 6 depicts two curves in this regard. One of the curve represents the maximum power that be extracted from the PVG (i.e such curve is no more than the representation of the left column of Table A.1 of the appendix) while the second curve represents the generated power delivered by the PVG source.

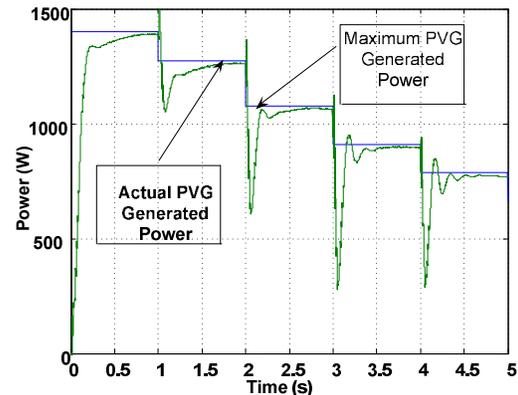


Figure 6: System Performance: Power Generated by the PVG Source and Maximum Power that can be extracted from the PVG source.

Insolation Level (%)	PVG Source Generated Power (W)	PVG Source Maximum Generated Power (W)	Matching Factor (%)
100	1388.0	1400	99.14
90	1259.1	1272	98.98
80	1060.9	1077	98.50
70	892.6336	910.2	98.07
60	767.6625	784.7	97.83

At this point, it is worth mentioning that based on the depicted curves in figures 5 and 6 and on the screened results in Tables 1 and 2, one can conclude that the objectives of this investigation are met when operating the bridge rectifier in the inverter mode.

The drawbacks that might be expected from the implementation of this idea is the confrontation with the power quality issue. Such issue consists of noting the distortion in voltage and current signals at the AC side of

figure 1. Signal distortion creates adverse effects on the sensitive loads that may replace the resistive load connected at the PCC point. Currents and voltages waveforms are recorded when simulating the developed SIMULINK diagram of figure A.1. Figure 7 visualizes the waveforms of the voltage at the point of common coupling (PCC) at 100% and 60% insolation levels. The total harmonic distortion factor (THD) was computed and it was found to be 13.51 % and 9.67 % at 100% and 60% insolation respectively. Such results are clearly exceeding the limits set by Power Quality Standards like the well known IEEE standard [7].

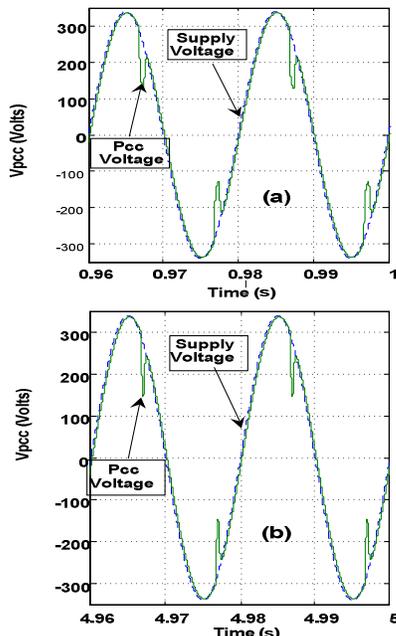


Figure 7: System Performance: PCC Voltage Waveforms a) Under 100% Insolation Level b) Under 60% insolation Level.

Figure 8 depicts the main AC supply current and the AC load currents waveforms at 100% and 60% insolation levels. For the main AC supply current, the total harmonic distortion factor (THD) was computed and it was found to be 41.26 % and 27.33% at 100% and 60% insolation respectively. For the load current, the total harmonic distortion factor was found to be 13.51 % and 9.67 % at 100% and 60% insolation respectively. current.

The levels of the total harmonic distortion factor encountered whether in the voltage waveforms or in current waveforms exceed the allowed limits stated in a number of standards like standard of reference [7]. Besides the encountered problems with power quality, the power factor at the main AC supply bus was also found to be low, in particular at higher insolation levels when the PVG contributes more power to the AC load. Therefore, future extension of follow up to the current investigation is to come-up with active voltage or current conditioners, and power factor correctors that will serve at reducing the harmonics and improving the power factor level. In doing so, four objectives will be met 1- Effectiveness contribution of the PVG to AC grid systems, 2- Maximum extraction of power from PVG system, 3- Qualitative

control of voltage and current waveforms, and 4- Positive improvement of power factor.

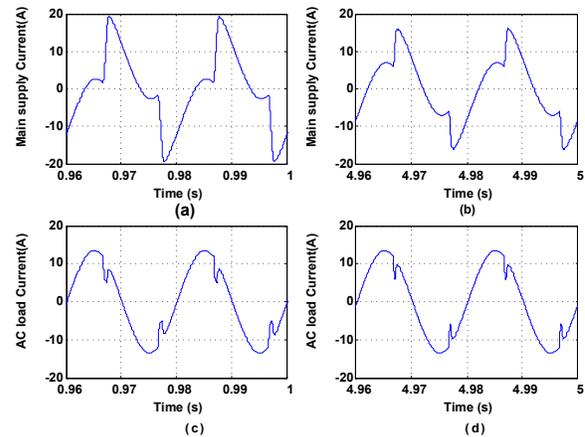


Figure 8: System Performance: a) Main AC Supply Current Waveform under 100% Insolation Level b) Main AC Supply Current Waveform under 60% insolation Level c) AC Load Current Waveform under 100% Insolation Level d) AC Load Current Waveform under 60% insolation Level..

4. Conclusion

Interconnecting PVG source to a main AC supply has been investigated in this paper. The interconnection has been done using a bridge rectifier working in the inverter mode of operation.

A Matlab/SIMULINK model for the idea of interconnection has been developed to check the idea claims. Quite encouraging results were reached for five possible insolation levels. For an almost 2kW power required by an ac load connected at the ac side of the bridge, the PVG source contributed nearly 66 % of such power while the main ac supply supplied the rest 34% of power to the AC load. The reader might question such claims but the author would like to clarify that this has occurred because the maximum possible power from the used PVG is 1.4 kw which is comparable to the required AC load (2 Kw). Thus, if the same PVG source is used in other circuits in which the AC load may require 20 kw for instance, the contribution from the PVG source to the source will be at most $(1.4/20 \times 100 = 7\%)$ and the remaining 93% of load power will be provided by the main AC supply. Similarly, if the same PVG source is used while the AC load requires only 1 Kw for instance, the PVG will cover 100% of the AC load power and moreover it will pump 400 W into the main AC supply.

Besides proving the effectiveness of interconnecting the PVG source to AC grid, maximum power extraction from the PVG source has been also targeted in this investigation for five pretended insolation levels. This has been through a self-adjusted firing angle controller in the MALAB/SIMULINK environment. Simulation results show that a 99 % matching factor between the maximum PVG power and the delivered PVG power are reached at a pretended 100% insolation level.

The encountered drawback after analyzing the quality of the obtained voltage and current waveforms is the

generation of tremendous distortion in the concerned waveforms and low power factor levels. Therefore, the last worry is among the tasks or recommendations that will be investigated by the author in the near future.

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Appendix

A.-1: Study System Parameters:

Insolation Level (%)	Maximum PVG Power Pg, Max (W)	Photocurrent I _{ph} (A)	Open Circuit Voltage Voc (V)
100	1388.0	13.61	176
90	1272	12.5	174
80	1077	10.78	170.5
70	910.2	9.31	167
60	784.7	8.2	164
50	663.7	7.08	160.5
40	456.6	5.15	153

Insolation Level (%)	Maximum PVG Power Pg, Max (W)	A (Ω)	B (1/AV) *10 ³	C (1/A)
100	1388.0	12.94	0.119	0.0819
90	1272	13.96	0.129	0.089
80	1077	15.81	0.165	0.1047
70	910.2	17.95	0.182	0.1198
60	784.7	20.01	0.209	0.1359
50	663.7	22.70	0.247	0.1573
40	456.6	29.71	0.2386	0.2022

Table A-2: Other Parameters Values

AC side	Main AC source	Voltage: 240 V, 50 Hz	Inductance= 5 mH
	Transformer	Resistance= 0 Ω	Inductance= 5 mH
	AC Load	Resistance= 25 Ω	Inductance= 0 mH
DC side	Smoothing reactor	Resistance= 0 Ω	Inductance= 500 mH

A-2: PVG Maximum Power

The maximum power of the PVG (Pg, max) is calculated as follows:

The derivative of equation (4) with respect to the voltage V_g is found and set to zero.

That is:

$$\frac{dP_g}{dV_g} = \frac{d}{dV_g} \left[\frac{V_g (V_{oc} - V_g)}{A + BV_g^2 - CV_g} \right] = 0. \quad (A.1)$$

When expanding and simplifying such derivative, the following quadratic equation is expected:

$$\alpha V^2 + \beta V + \lambda = 0 \quad (A.2)$$

Where

$$\alpha = C - B * V_{oc}, \quad \beta = -2A \quad \text{and}$$

$$\lambda = A * V_{oc}$$

The solution of equation (A.2) gives the PVG voltage:

$$V_{g, \max} = \frac{-\beta - \sqrt{\beta^2 - 4\alpha\lambda}}{-2\alpha} \quad (A.3)$$

The PVG current corresponding to this voltage can be calculated from equation (2) in this paper:

$$I_{g, \max} = \frac{(V_{oc} - V_{g, \max})}{A + BV_{g, \max}^2 - CV_{g, \max}} \quad (A.4)$$

Hence the maximum PVG power (Pg,max) can be calculated as:

$$P_{g, \max} = V_{g, \max} \frac{(V_{oc} - V_{g, \max})}{A + BV_{g, \max}^2 - CV_{g, \max}} \quad (A.5)$$

Based on the Parameters values of Table A.1, the maximum power that can be extracted from the PVG used in this paper at different insolation levels are shown in the second column of Table A.1.

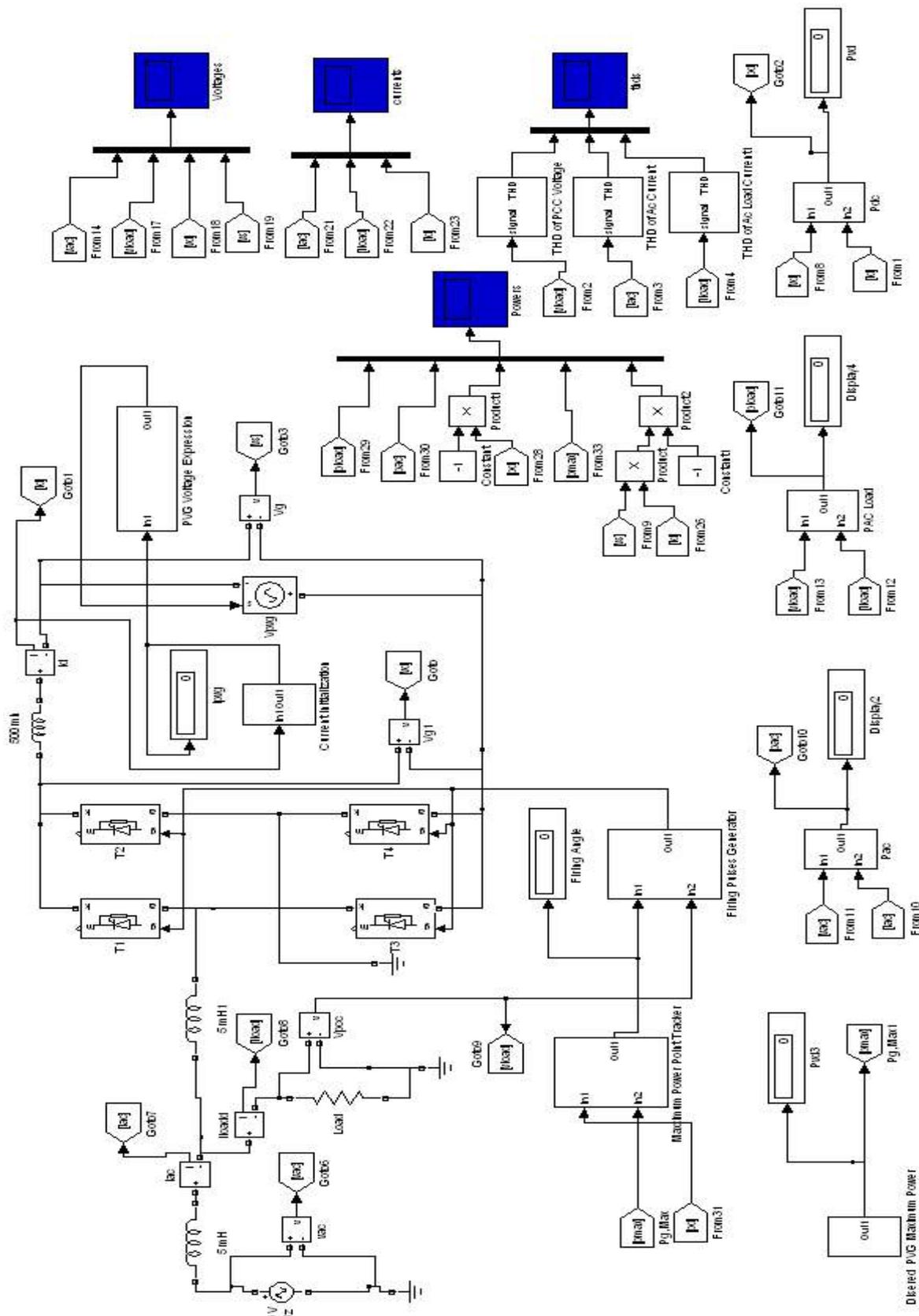


Figure A.1: SIMULNK Model of the System Under Study