Analysis and Validation of Power Conversion Efficiency in PV System.

G.C. Asomba, Ph.D.[1] **and C.A. Nwosu, M.Eng.**[2]

[1]Department of Electrical Engineering, University of Nigeria, Nsukka, Nigeria.
E-mail: grg_chira@yahoo.com

[2]Department of Physics and Astronomy, University of Nigeria, Nsukka, Nigeria.
E-mail: cajethannwosu@yahoo.com

ABSTRACT

The result of a conducted study on the amount of alternating current (AC) power from 6 parallel connected inverters supplied from 180 photovoltaic (PV) panels located in Electrical Power System Laboratory of Delft University of Technology (TU-Delft), the Netherlands, is presented. Data which included the powers and temperatures of both the inverters and the PV array were recorded over 60 minutes at 10 minutes intervals by a programmable logic controller (PLC) and personal computer (PC) which formed part of the system. The results show that between 7% and 19% of power generated in the PV array are short supplied to the AC bus through the inverters. The derate factors, a measure of losses and efficiencies, of the components of the PV system are believed to be responsible for the difference in PV power and the power supplied to the bus through the inverters.

(Keywords: photovoltaic, PV, inverters, losses, efficiency)

INTRODUCTION

Photovoltaic (PV) power supplied to the utility grid or directly to the consumer is gaining more and more visibility due to many national and international incentives [1]. Together with other renewable energy technologies, photovoltaic energy is gaining acceptance as a way of maintaining and improving living standards without harming the environment. Many PV arrays are designed as stand-alone systems that are equipped with batteries to store electricity for sunless hours and operate completely independent of the grid. However, grid-connected PV, in which PV backs up or supplements the grid power, represents the fastest growing market segment today, already comprising about 40% of current PV sales according to the industry statistics [2].

PV science is the science of turning energy produced from the sun into electricity. Outside the atmosphere, the intensity of solar radiation is about 1,300 W/m^2. When this energy is passed through the Earth's atmosphere, photons are scattered and absorbed by particles in the sky, like clouds or haze. Depending on the area, more than 90% of the solar radiation can reach the ground [2]. For effective and wider utilization of PV power, the direct current (DC) output has to be converted to alternating current (AC) supply. The main challenge for engineers and scientists at present is conversion efficiency [3]: converting the sun's energy to DC output and then to AC supply. The conversion from DC power to AC power usually results in an energy decrease from approximately 6%-10%, and varies for each inverter (primarily due to energy lost in the form of heat).

Several technologies, each of which may be applied singly or which may be used in a combined manner, depending on design topology, to realize maximum PV power, have been reported in the literature. Some of these technologies are inherent in the fabrication of the PV cells that make up the modules while others are outside the PV cells. Among the technologies inherent in the PV fabrication (with respect to PV module light-to-electricity efficiency) are crystalline silicon cells (η = 10% - 15%), multi-crystalline silicon cells (η = 9% - 12%). Other types are: thin-film amorphous silicon (η = 10%) [4], thin-film copper indium diselenide (η = 12%), and thin-film cadmium telluride (η = 9%). Technologies outside the PV cells include maximum power point tracking (MPPT) control algorithms either on the DC or AC side, the choice of interface between solar cells, or between modules (by use of bypass diodes), the choice of interconnection of the modules [4]-[6]. Irrespective of the adopted technology which may depend on application and cost, the overall objective of a design is achieved if the PV power output is efficiently converted to AC power supply for remote loads or grid connection. Inverters are used to convert DC output power to AC power supply. The amount of DC power the inverter is capable of converting to AC power supply depends on the efficiency of the inverter. The overall efficiency figure, however, hinges on both the efficiency of the solar panels and also on how well the DC output is converted to a practical AC supply by the inverter circuit.

This paper presents the result of a conducted study on the amount of AC power from 6 parallel connected inverters supplied from 180 PV panels located in Electrical Power System Laboratory of Delft University of Technology (TU-Delft), the Netherlands. Two strings of panels are connected in parallel to each inverter, with each string having a total of 15 modules in series. The 6 inverters are connected in parallel to the asymmetric bus of the power plant. The plant is a stand alone Wind-Solar hybrid renewable energy power plant with batteries and combined heat and power (CHP) backups capable of supplying green power to about 15 households in a developed economy or about 100 households with an average of 400 W per household in rural community.

ANALYSIS OF THE PV ARRAY

In a whole PV array, there are several strings in parallel. A string consists of several PV modules in series. Series wiring increases voltage while parallel wiring increases capacity. Figure 1 shows PV power conversion chain consisting of paralleled **m** by **n** PV arrays (**m** stands for number of modules in series while **n** is for the number of strings in parallel) connected to one inverter. In our case study, **m** is 15 while **n** is 2 making a total of 30 PV modules connected to one inverter. Six of such units supply power to the bus.

The current–voltage characteristic equation (I–V) of PV arrays is based on the Shockley equation for a diode [2]:

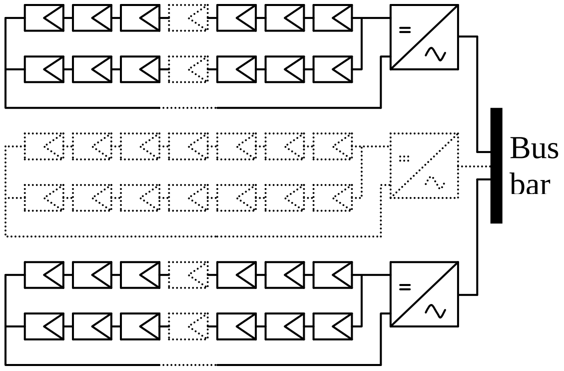


Figure 1: PV Power Conversion Chain**.**

$$I = I_0\left[\exp\left(\frac{qV}{kT}\right) - 1\right], \qquad \textbf{(1)}$$

but including other parameters to better describe the measured data from the PV array we have:

$$I = n_p I_{ph} - n_p I_{rs}\left[\exp\left(\frac{q(V + R_S.I)}{A.n_s.k.T}\right) - 1\right] - \frac{V + R_S.I}{R_{Sh}}$$

(2)

where I is the PV array output current (A), V is the PV array output voltage (V), n_s is the number of cells in series, n_p is the number of strings connected in parallel, q is the charge of an electron, k is Boltzmann's constant, A is a p-n junction ideality factor, T is the cell temperature (K), I_{ph} is the cell photo current, I_{rs} is the cell reverse saturation current (A), R_S is the series resistance (Ω), and R_{Sh} is the shunt resistance (Ω) [5]. The factor A determines the cell deviation from the ideal p-n junction characteristics. The ideal value ranges between 1 and 5. These data will be evaluated using the values for the short circuit current, open circuit voltage and maximum power point of the I–V characteristic given by the manufacturer. The cell reverse saturation current I_{rs} varies with temperature according to the following equation:

$$I_{rs} = I_{rr}\left[\frac{T}{T_r}\right]^3 \exp\left(\frac{qE_G}{kQA}\left[\frac{1}{T_r} - \frac{1}{T}\right]\right) \qquad \textbf{(3)}$$

where Q is the electron charge, T_r is the cell reverence temperature, I_{rr} is the reverse saturation current at T_r, and E_G is the band-gap energy of the semiconductor in the cell. The photocurrent I_{ph} depends on the solar radiation and the cell temperature as shown in the following equation:

$$I_{ph} = \left[I_{scr} + k_i\left(T - T_r\right)\right]\frac{S}{100} \qquad \textbf{(4)}$$

where I_{scr} is the cell short-circuit current at reference temperature and radiation, k_i is the short-circuit current temperature coefficient, and S is the solar radiation in mW/cm$_2$.

A relationship which exists between PV module temperature and the amount of power generated by the PV system is such that increase in module temperature leads to decrease in module power. Module operating temperature increases when placed in the sun. As the operating temperature increases, the power output decreases (due to the properties of the conversion material - this is true for all solar modules). The PV Test Condition (PTC) ratings take this into consideration by calculating the PTC ratings based primarily on the specific module temperature characteristics. The PTC ratings are different for each module, and can vary from approximately 87%-92% of the Standard Test Conditions (STC) rating. A typical decrease in power output is approximately 12% for crystalline based solar modules. This decrease results in a STC rated 100 Watt DC solar module being PTC rated at approximately 88 Watts DC.

For practical use, a certain number of PV modules need to be connected to meet the user's demand on voltage and power. The total number for serial connection is determined by the operating DC voltage of the system, while the number of PV modules for parallel connection determines the capacity of the PV array. The voltage V_{PVA} of the PV array is:

$$V_{PVA} = N_{PVS} \cdot V_{PV} \qquad \textbf{(5)}$$

and the power output P_{PVA} of the PV array is:

$$P_{PVA} = N_{PVP} \cdot N_{PVS} \cdot V_{PV} \cdot I_{PV} \cdot F_{con} \cdot F_{oth}, \quad \textbf{(6)}$$

where N_{PVS} is the serial connection number of the PV modules; N_{PVP} is the parallel connection number of the PV module strings; and F_{con} and F_{oth} are the factors representing connection loss and other losses such as the loss caused by accumulative dust, etc.

The PV inverters may be seen as integral part of the PV power unit since the PV arrays and the inverters combine to supply AC power to a common bus. Six inverters are connected in parallel to the bus.

MODELING OF LOSSES IN PV ARRAY

Modeling and analysis of PV array is important in order to approximately account for the losses in the PV array. To achieve this, the PV array is divided into stages. The first stage is modeling a cell, second is about a module, third is about a string, and the last stage is modeling the whole array. The first and the last stage modeling are considered in this paper as the intermediate stages are inherently represented in the PV array modeling.

Modeling of a PV Cell

Usually, a PV cell may be estimated with resistors and a capacitor as shown in Figure 2 [7]. R_s is the series resistance, R_p is the parallel resistance, and C_d is the parallel capacitor. With this model, the cell impedance Z is described as:

$$Z = R_s + \frac{R_P}{j\omega C_P R_P + 1} \qquad \textbf{(7)}$$

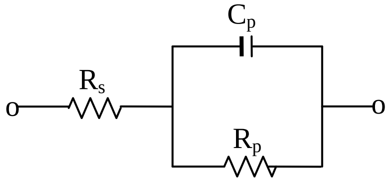


Figure 2: Equivalent Circuit of a PV Cell.

Modeling of a Whole PV Array

A whole PV array consists of several strings in parallel. A string consists of several PV modules in series, while a PV module is a number of PV cells. The wiring in a PV module is several meters long. This demands that the line inductance in and between modules should be accounted for. In a whole PV array, the ground model between the array and the ground and the static capacitance to the infinite distance are usually taken into account [7]. As shown in Figure 3, the static capacitance to the infinite distance is represented with C_o, while the ground model is described with resistors and a capacitor. R_S represents the combination of module series resistance and line series resistance.

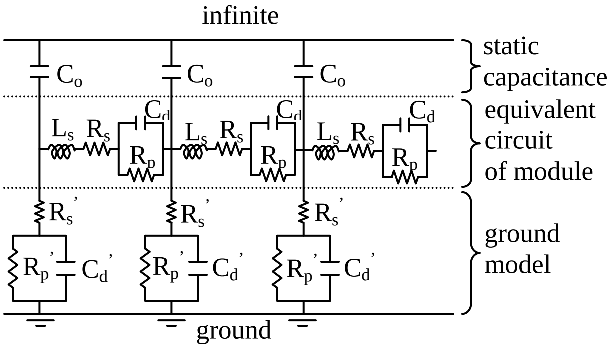


Figure 3. Equivalent Circuit of a PV Array [8].

MODELING OF LOSSES IN PV ARRAY AND INVERTER

Usually PV array is mounted on roof tops several meters from the inverters and the point of utilization of the power. Three stages of losses considered here are PV array losses, line losses, and inverter losses. The total array losses is modeled by Z_{PV}, losses in line inductance L_L and resistance R_L, may be modeled by $Z_{L,}$ while inverter losses is modeled by Z_I. Figure 4 shows a model block diagram representation of the losses.

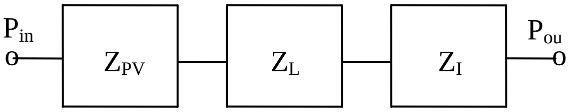


Figure 4: A Model of Losses in PV/Inverter System.

Switching losses and losses due to non-ideal components result in increase in temperature in the converter systems.

DC to AC Derate Factor

At Standard Test Conditions, a factor known as DC to AC derate factor, which accounts for the losses and efficiencies of components of a PV system is considered. The DC to AC derate factor is the mathematical product of the derate factors for the components of the PV system. The nameplate DC power rating of the PV system is multiplied by an overall DC to AC derate factor to determine the AC power rating at STC. In most cases, the overall default value of plus or minus 0.77 is used to provide a reasonable estimate for modeling the energy production. The components that constitute a whole PV system include [5] PV module nameplate DC rating, inverter and transformer, mismatch, diodes and connections, DC wiring, AC wiring, soiling, system availability, shading, sun-tracking, and age.

DATA COLLATION

The power plant which the PV system is part of comprises an interconnection of a number of functional units and auxiliary components in order to produce green power for a number of households. To monitor and record information for the input and output signals within the system, a number of transducers and recording devices were installed at strategic positions.

Input and output powers in the system were programmed into programmable logic controller and PC so that second-by-second and minute-by-minute information is monitored, processed, and stored. Information and data for this paper was gathered from the system PC. Data was collated on the unit over a time to determine, among other things, the variation of module power over a day, the variation of module power and temperature, the output power from the PV array and the percentage of this power the inverters were capable of delivering to the bus.

Table 1 is the data for the PV modules. To determine the level of power output from the PV array and the percentage of this power the inverters were capable of delivering to the bus, data which included the temperatures of both the inverters and the PV array were recorded over 60 minutes at 10 minutes intervals. Table 2 shows the data from the PV array which included the total power calculated using the measured PV power per square meter and the area of each PV module 51cm by 114cm. Table 3 shows the data from the inverters which include average temperatures, power and energy output of the inverters.

Table 1: The PV Modules Data.

Open circuit voltage (V_{oc})	21.3V
Short-circuit current (I_{sc})	4.4A
Maximum power	68W
Maximum voltage (V_p)	16.5V
Tolerance on peak power	± 4%

Table 2: PV Array Data.

Step	Temp. (°C)	PV power (W/m^2)	Total power (W)
1	34.921	22.064	2309.04
2	28.262	26.842	2809.08
3	30.825	75.765	7929.00
4	32.877	96.040	10050.84
5	33.291	84.682	8862.12
6	33.615	95.470	9991.08

Table 3: Inverter Data.

Step	Temp. (°C)	Total power (W)	Energy (J)
1	56.8	1937	4554280
2	52.7	2276	4554870
3	59.5	7368	4556140
4	60.0	9361	4557510
5	58.8	7955	4559020
6	59.0	9007	4560550

Figure 5 shows the variation of power per square meter of a PV module over 24 hours. In Figure 6, the variation of module power per square meter and temperature over a day is displayed. Data from Tables 2 and 3 are used to illustrate the variations in temperature and power in the PV array and in the inverters.

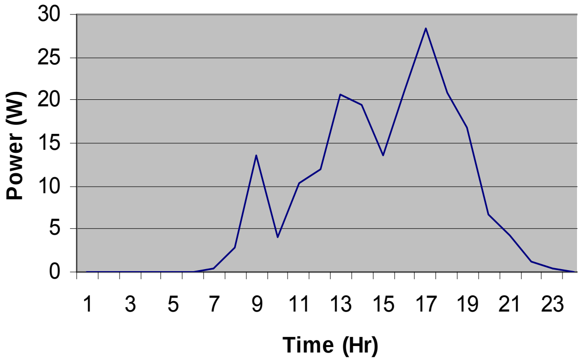


Figure 5: Variation of Module Power per Square Meter over a Day.

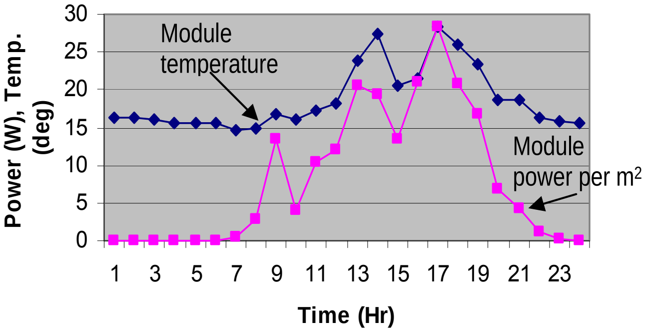
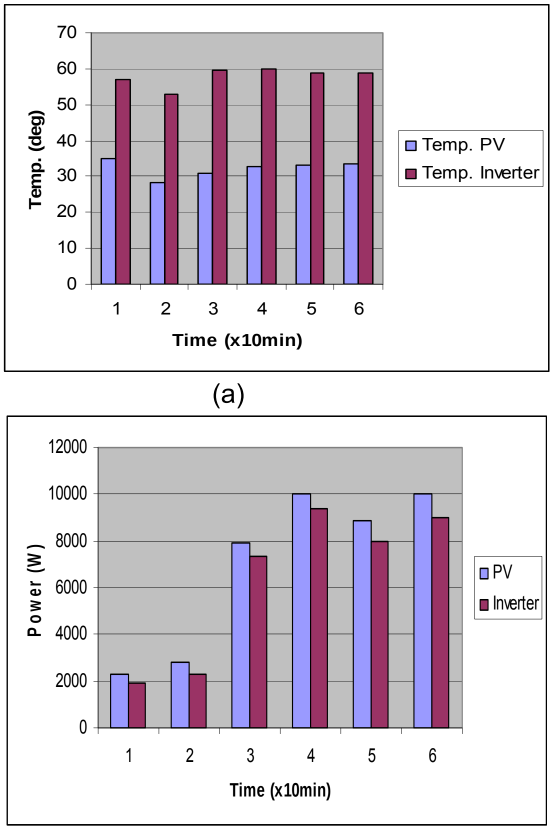


Figure 6: Variation of per m^2 Module Power and Temperature over a Day.



(a)

(b)

Figure 7: Variation of Temperature and Power in PV Array and in Inverters Over an Hour. (a) Temperature Variation, (b) Power Variation.

DISCUSSION OF RESULTS

The data for the experimental verification was got from a winter-summer-autumn environment of the Netherlands, where in most cases, the solar irradiation starts to peak as from 1200 hours to around 1800 hours as indicated in the module power and temperature of Figure 5. From the same Figure 5, it is observed that both the module power and temperature peaked around 1600 hours with a somewhat direct relation between the two between 1500 and 1600 hours. However, to ascertain the level of power output from the PV array and the percentage of this power the inverters were capable of delivering to the bus, data which included the temperatures of both the inverters and the PV array recorded over 60 minutes at 10 minutes intervals are as displayed in Tables 2 and 3.

The decrease in module power as a result of increase in module temperature (a factor of properties of the PV conversion material), is evident in the data of Table 2 and in Figure 6. From Table 2 (sixty minutes recorded data), the total PV array output power which peaked at about 32.9 C to about 10.05kW nosedived to about 8.9kW even as the temperature increased to about 33.3 C. The factor of properties of conversion material is also evident in Figure 6 between 1200hrs and 1300hrs. The PV module power which peaked to 20.6W/m^2 at about 23.8 C, dropped to 19.4W/m^2 at about 27.3 C.

Variations in temperatures and powers in the PV array and inverters are clearly shown in Figure 7. From Figure 7(a), it is easily observed that the average temperatures in the PV inverters are almost twice the temperatures in PV array, even as the modules are in direct contact with sunlight. From Figure 7(b), it is observed that power generated from the PV array at any given period is higher than the power delivered to the bus through the inverters. In equation 6, F_{con} and F_{oth} have been defined as factors representing connection loss and other losses such as the loss caused by accumulative dust etc. In this case, power losses which range between 7% and 19% may be accounted for by the losses in the array and line and the efficiency and losses in the inverters. All these losses may be summed up in the derate factors of the components that make up the entire PV system.

CONCLUSIONS

In this paper, the level of power output from a PV array and the percentage of this power the inverters were capable of delivering to the bus has been verified to validate the existing norms. Between 7% and 19% of power generated in the PV array are short supplied to the AC bus through the inverters. These percentages of power loss may be accounted for by the derate factors, a measure of losses and efficiencies, of the components of the PV system.

REFERENCES

1. Blaagjerg, F., Z. Chen, and S.B. Kjaer. 2004. “Power Electronics as Efficient Interface of Renewable Energy Sources”. *IEEE Power Electronics and Motion Conference*. 3:731 – 1739.

2. Shahidehpour, M. and F. Schwarts. 2004. “Let the Sun go Down on PV [photovoltaic system]”. *IEEE Power and Energy Magazine*. 2(3):40 – 48.

3. Schiel, M. 2007. “Inverting Energy Concerns Through Efficient Designs”. *Future Technology Magazine*. March 2007:1 – 5.

4. Blaagjerg, F., Z. Chen, and S.B. Kjaer. 2004. “Power Electronics as Efficient Interface in Dispersed Power Generation”. *IEEE Trans. on Power Electronics*. 19(5):1184 – 1194.

5. Yu, G.J., Y.S. Jung, J.Y. Choi, and G.S. Kim. 2004. “A Novel Two-Mode MPPT Control Algorithm Based on Comparative Study of Existing Algorithms”. *Science Direct – Solar Energy*. 76(4):455 – 463.

6. Nguyen, D.D. and B. Lehman. 2006. “Modeling and Simulation of Solar PV Arrays under Changing Illumination Conditions”. *IEEE COMPEL Workshop*. Rensselaer Polytechnic Institute: Troy, NY. July 16 – 19, 2006. 295 – 299.

7. Takashima, T., K. Otani, and K. Sakuta. 2003. “Electrical Detection and Specification of Failed Modules in PV Array”. *3rd World Conference on Photovoltaic Energy Conversion*. May 11 – 18, 2003. Osaka Japan. 2276- 2279.

ABOUT THE AUTHORS

George C. Asomba, Ph.D. is in the Department of Physics and Astronomy, University of Nigeria, Nsukka, Nigeria. His research interests are Condensed Matter and Materials Science (magnetism, superconductivity, nanoscience and nanotechnology) and Solar Energy (photovoltaic and renewable energy). Asomba is married with children.

Cajethan A. Nwosu obtained his B.Eng. and M.Eng. degrees in Electrical Engineering from University of Nigeria, Nsukka, Nigeria, in 1994 and 2004 respectively. He is presently working toward the Ph.D. degree in Electrical Engineering. He is currently a lecturer in the Department of Electrical Engineering, University of Nigeria, Nsukka, Nigeria. His research interests include power electronic converters and renewable energy technologies.

SUGGESTED CITATION

Asomba, G.C. and C.A. Nwosu. Asomba. 2008. “Analysis and Validation of Power Conversion Efficiency in PV System”. *Pacific Journal of Science and Technology.* 9(2):337-343.

Pacific Journal of Science and Technology