Grid Connected Photovoltaic System

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***Abstract*- Renewable energy resources such as Solar, wind and hydro are pollution free, easily erectable, and limitless so they represent reliable alternatives to conventional energy sources e.g. oil and natural gas. However, the efficiency and the performance of these systems are still under development. Among them, Photovoltaic systems are mostly used as they are light, clean and easily installable. This systems connection to the grid requires special conditions to obtain a high-quality electric power system. This paper presents interfacing of three phase grid connected PV system. DC-DC boost converter with maximum power point tracking (MPPT) is used to extract the maximum power obtained from the sun and transfer it to the grid. In any PV based system, the inverter is a critical component responsible for the control of electricity flow between the dc source, and loads or grid so a voltage source inverter (VSI) is used to convert the dc power into AC power before injecting it into the grid. A comprehensive simulationnand implementation of a three-phase grid-connected inverter are presented to validate the proposed controller for the grid connected PV system.**

***Keywords*- Renewable energy, PV modules, Photovoltaic system, boost converter, voltage source Inverter, MPPT control, Grid.**

I. INTRODUCTION

Energy demand is increasing day by day due to increase in population, urbanization, and industrialization, renewable energy resources are alternatives to our traditional energy sources which are limited and will expire. Clean energy resources such as solar, wind and hydro became more and more popular mainly because they produce no emissions and are inexhaustible. The photovoltaic (PV) energy effect can be considered an essential sustainable resource because of solar radiant energy abundance and the sustainability thus grid connected photovoltaic system is widely used, although solar energy is available abundantly and free of cost, the cost of the photovoltaic cells is very high. Hence the initial investment on solar energy will be very high. The basic element of a PV system is the solar cell which converts the solar irradiance into direct current. Grid interconnection of PV system requires an efficient converter to converter the low DC voltage into AC.

The technical requirements from both the utility grid side and the PV system side need to be satisfied to ensure the safety of the PV installer and the reliability of the utility grid to utilize the generated power effectively. An interface system must be developed to make the interconnection between the PV system and the grid. To ensure that the system will work as desired and to investigate its impact in different conditions; the system must be modelled and simulated. This paper is a small contribution in this area but furthermore, researchers and projects must be done for implementation of grid-connected PV systems and smart grids in Sudan. So, the main objective is developing a power electronics interface for a three-phase grid connected PV, capable of extracting maximum power from the PV arrays at all insolation levels and Implementation of the inverter to convert the dc output voltage to a voltage compatible with the utility grid and house appliances.

GRID CONNECTED PV SYSTEM

A. Elements Included in a System of Photovoltaic Conversion

The basic schematic diagram of a grid connected PV system with voltage source inverter is shown below.

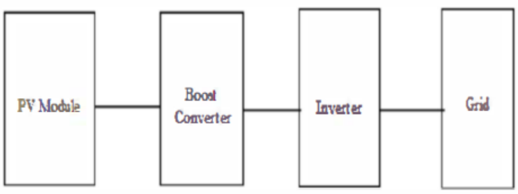

Fig. 1. Grid connected PV system block Diagram

The main elements that can be included in a system of photovoltaic conversion are Photovoltaic modules, converters, utility grid, loads DC and AC, and Inverters [2]. It is an arrangement used in PV standby power supply units, it's called grid connected system without a battery backup. Although systems with battery backup confront the issue of reliability of the grid supply but it is more complicated and more expensive.

i) PV module

The solar panel is the power source of all photovoltaic installation. It is the result of a set of photovoltaic cells in series and parallel. PV cell directly converters the solar irradiance into electricity in the form of dc when sunlight interacts with semiconductor materials in the PV cells. Figure (2) shows the equivalent circuit of a PV, from which non linear I-V characteristic can be deduced. Hence, the cells are connected in series and in parallel combinations in order to form an array with desired voltage and power levels, solar cells are combined to form 'modules' to obtain the voltage and current (and therefore power) desired [2].

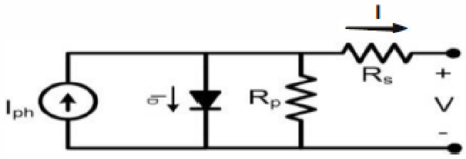

Fig. 2. Equivalent circuit of photovoltaic cell

2) DC-DC Boost Converter

The positioning of the boost converter will improve the whole photovoltaic installation, allowing different controls from the system. Depending on the applied regulation, the panels will contribute to the maximum energy given to the system or the optimal energy for their operation. The boost converter is a medium of power transmission to perform energy absorption and injection from solar panel to grid-tied inverter. The process of energy absorption and injection is performed by a combination of four components which are an inductor, electronic switch, and diode and output capacitor [3]. The connection of a boost converter is shown in figure (3).

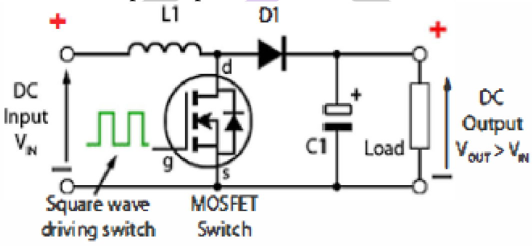

Fig. 3. Basic Boost Converter Circuit

When switch is closed for time t l, the inductor current rises and energy is stored in inductor L. If the switch is open for time t2, the energy stored in the inductor is translated through diode D and inductor current falls, the switching duty cycle a is defined as the ratio of the on duration to the switching time period so the output voltage is greater than the input voltage and is expressed as in eq. (1)

$$Vout/Vin = 1/(1-\alpha) \qquad (1)$$

3) Inverter

It is the main part of the system which is consists of semiconductor switches with a controller that provides the right switching pulses to control the inverter. It converts the DC power produced by the PV array into AC power consistent with the voltage and power quality required by the utility grid.

The inverter topology selected for this design is the voltage source inverter (VSI). Figure (4) shows a schematic diagram of a 3 phase VSI. It is composed of six switches SI through S6 with each phase output connected to the middle of each "inverter leg". Two switches in each phase are used to construct one leg. The AC output voltage from the inverter is obtained by controlling the semiconductor switches ON and OFF to generate the desired output [4].

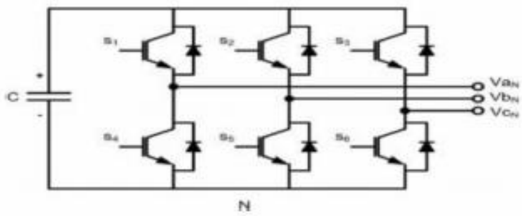

Fig. 4. Topology of Three Phase Inverter

The AC output waveforms shape and quality are directly related to how the conduction intervals of the switches are controlled. The method chosen for this application was sinusoidal pulse width modulation (SPWM), it allows the control of the phase, magnitude, and frequency of the generated AC waveform. It requires three reference sinusoidal waveforms (for three phase operation) of the same frequency as the desired output waveform and one high frequency triangle waveform known as the carrier signal. The process is done by comparing the magnitudes of the sinusoidal and triangle waveforms. When the amplitude of the modulating signal is greater than that of the carrier signal, the upper switch in the corresponding phase leg in figure (4) is activated. This leads to the output voltage having the same magnitude of the DC link voltage and the vice versa. The magnitude of the output phase voltage (RMS) can be determined using eq. (2). Where ma is the modulation index and calculated as in eq. (3).

$$V_{rms} = m_a \frac{V\_Dc}{2\sqrt{2}} \tag{2}$$

$$m_a = \frac{V_m}{V\ carrier} \tag{3}$$

4) Other Devices
like filter can also be used for a better performance, a meter could be used to account for the energy being drawn from or fed into the local supply network.

5) Load
It is the component responsible for absorbing this energy and transforming it into work.

6) Grid modelling
The unit formed by the energy transport line and all the connection transformers between the various voltage levels, will be indicated by network in figure (5).

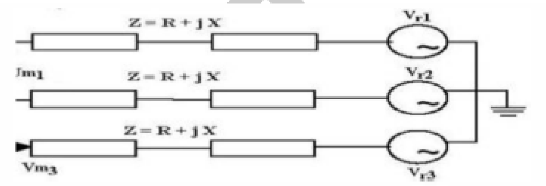

Fig. 5. Grid equivalent circuit

The conditions for proper interfacing between the two systems are discussed below:

• Phase sequence for the solar system and grid should be matched otherwise synchronization is not possible. The three phases should be 120 dig phase apart for both systems.

• Frequency matching: generally, grid is of 50 Hz frequency, now if the solar system's frequency is slightly higher than grid frequency (0.1 to 0. 5) synchronization is possible but it should not be less than grid frequency.

• Voltage matching: one of the vital points is the voltage matching. The voltage level of both systems should be the same [5].

As the capacity of PV systems is growing significantly, the impact of PV modules on utility grids cannot be ignored. Grid-connected PV systems can cause problems on the grid, such as injecting more harmonics or reducing the stability. This problem can be severe when a large-scale PV module is connected to the grid. Current harmonics produce voltage distortions, current distortions, and cause unsatisfactory operation of power systems [6].

B. METHODOLOGY
The system is composed mainly as following:
Photovoltaic array converts the sun irradiance and generates dc voltage and current, the DC-DC boost converter controlled by maximum power point tracking using (P&O) algorithm to track the maximum power point of the array
then the three phase Inverter converts the dc voltage to AC for grid interfacing or supply to the local load. The band pass filter removes harmonic components from the inverter output, the delta star transformer to step up the output voltage and to circulate zero sequences before connecting to the Utility grid and Control circuits to achieve the MPPT control, Synchronization, and Switching.

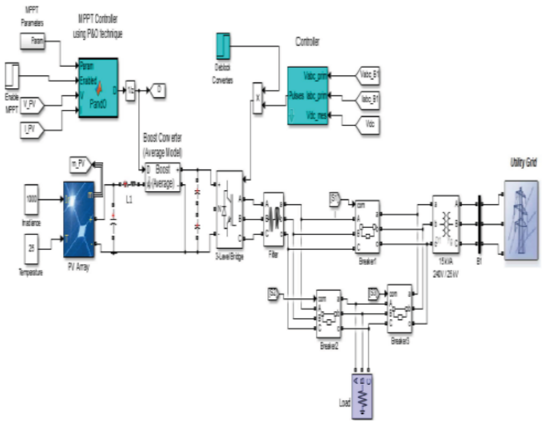

Fig. 6. MA TLAB model of grid-connected PV system

1) Solar Array Sizing:
It depends on the load requirements, solar irradiation, and geographical location, the proposed system is designed for a residence in Khartoum for example. The minimum size of the solar array was calculated to cover the housing demand which is assumed to be 61.42 KWh/day, to avoid the risk of under sizing, the process starts by multiplying the total average energy demand per day by a factor expressing the losses of the system components as in eq. (4) [7]

$$E_{array} = \text{daily average energy consumption} * 1.3 \qquad (4)$$

The irradiation data for a residence in Khartoum (LatI5.483, Lon32.643) is shown in table (1) [8]

TABLE I. Monthly Averaged Insolation Incident on a Horizontal Surface (kWh/m2/day)

Month	Jan	Feb	Mar	Apr	May	Jun
Insolation	5.35	6.09	6.84	7.29	6.94	6.98
Month	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Insolation	6.62	6.43	6.38	6.09	5.60	5.09

$$E_{array} = 61.42 * 1.3 = 79.846 \text{ kWh.}$$

Now the power of the solar array can be estimated by using eq. (5)

$$p = \frac{\text{daily energy requirement}}{\text{solar insolation}} = \frac{79.846 \text{ KWH}}{6.3} = 12.674 \text{ KW} \qquad (5)$$

Now the number of PV panels for the system and their connection in series and parallel.

No. of required PV modules by using eq. (6)

$$= \frac{\text{total power}}{\text{of single module}} = \frac{12.674 \text{ KW}}{249.86} = 50.724 \qquad (6)$$

approximated to 51 modules.
No. of modules connected in series by using eq. (7)

$$= \frac{\text{required output voltage}}{\text{at maximum power of single module}} = \frac{260}{31} = 8.387 \qquad (7)$$

Approximated to 9 module in series
No of module groups connected in parallel by using eq. (8)

$$= \frac{\text{total no of modules}}{\text{no.of modules connected in series}} = \frac{51}{9} = 5.6 \qquad (8)$$

Approximated to 6 groups.. (8)
The selected module characteristics are illustrated in figure (7).

ELECTRICAL DATA @ STC	TSM-235 PC/PA05	TSM-240 PC/PA05	TSM-245 PC/PA05	TSM-250 PC/PA05
Peak Power Watts-P_{MAX} (Wp)	235	240	245	250
Power Output Tolerance-P_{MAX} (%)	0/+3	0/+3	0/+3	0/+3
Maximum Power Voltage-V_{MP} (V)	29.3	29.7	30.2	30.3
Maximum Power Current-I_{MPP} (A)	8.03	8.10	8.13	8.27
Open Circuit Voltage-V_{OC} (V)	37.2	37.3	37.5	37.6
Short Circuit Current-I_{SC} (A)	8.55	8.62	8.68	8.85
Module Efficiency η_m (%)	14.4	14.7	15.0	15.3

Values at Standard Test Conditions STC (Air Mass AM1.5, Irradiance 1000W/m², Cell Temperature 25°C).
Power measurement tolerance: ±3%

2) Band bass filter and Transformer
They are connected between the inverter and the grid. The filter type is a band pass filter cantered at 50 Hz with very low band width. To meet IEEE 519 standard about harmonic injected in system. The delta star transformer was mainly introduced for voltage step-up and to trap the triple order harmonics.

3) MPPT Control
There is several MPPT control algorithms but based on MPPT efficiency, the Perturb and observe (P&O) is the most commonly used algorithm in commercial converters. This algorithm flow chart is shown in figure (8), where Vref in the represents the array voltage.

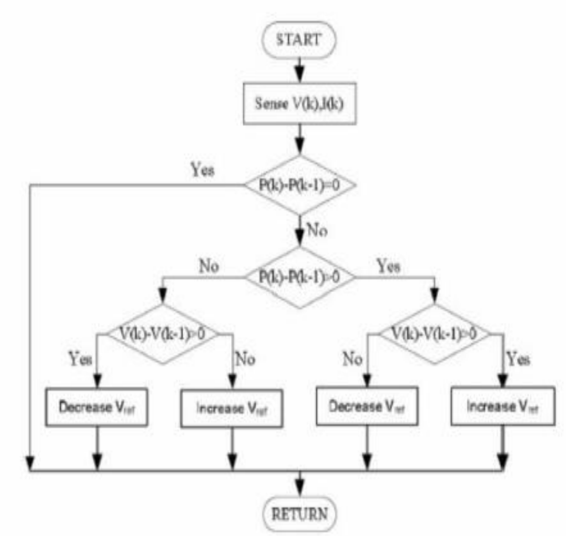

Fig. 8. Flow chart of P&O algorithm

P&O algorithm was implemented in MATLAB and the MPPT controller inputs were:
• Voltage and Current from the PV array.
• Maximum, minimum, Increment value and the initial value for duty cycle.

4) Control circuit
It takes grid parameter (voltage and current) and dc of boost converter for synchronization between grid and PV voltage. The aim of a control circuit to produced PWM signal for an inverter. The control circuit is shown in figure (9).

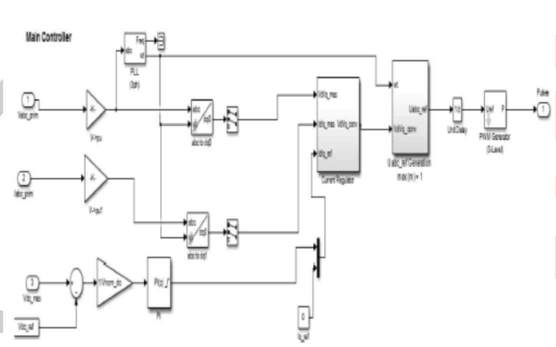

Fig. 9. Control Circuit

5) Switching System
To protect grid workers while maintenance and repair operations, the system is designed not to inject the power generated by the solar system to the house load instead of the grid if the grid is offline. Table (2) shows the logic for switching, '1' represents availability while '0' represents absence.

Table II. Switching logic

Enable	irradiance	Grid V	S1	S2	S3
1	1	1	1	0	1
1	1	0	0	1	0
1	0	1	0	0	1
1	0	0	0	0	1
0	X	X	0	0	1

Ill. RESULTS AND DISCUSSION

A. Simulation of the system with solar irradiance = 0

Figure (11) shows the voltages waveforms of the grid and the solar system when the solar irradiance was=O. As it shown, there was no voltage generated from the solar system when there was no solar irradiance.

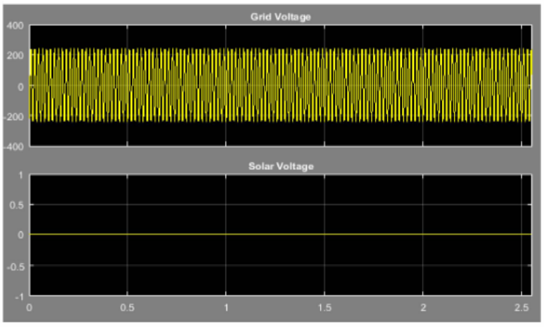

Fig. 1 1. Grid and Solar waveform when solar irradiance =0

B. Simulation of the system with grid voltage = 0 & solar irradiance=lOOO Wlm2

Figure (12) shows the solar and grid voltage waveform. When grid went, offline load was disconnected from the grid (switch S3 was opened) and connected to the solar System instead (S2 was closed).

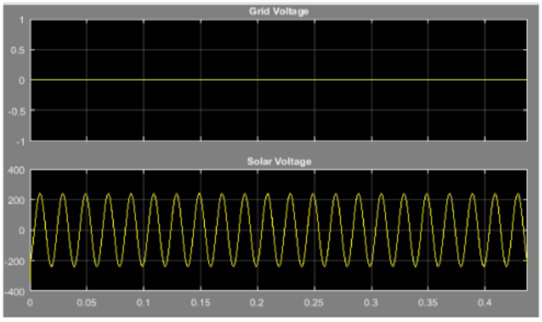

Fig. 12. Grid and Solar waveform when irradiance = 1000 and grid is off

C. Simulation of the system with solar irradiance = 1000 and grid voltage = 240V
The inverter output contains high order harmonics as shown in figure (13). The effect of filter observed clearly in figure (14).

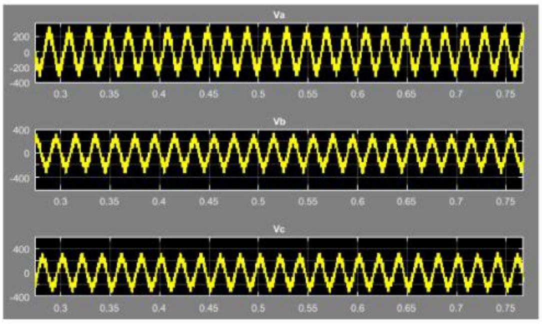

Fig. 13. Phase voltage waveform output of the inverter

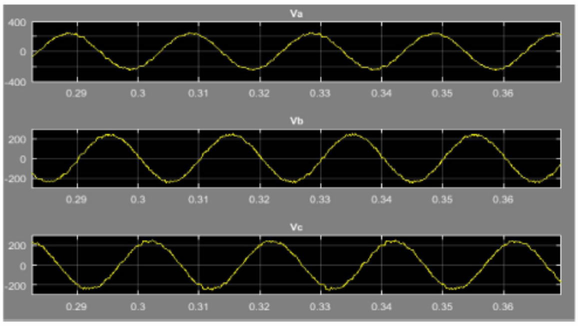

Fig. 14. Phase voltage waveform after filter

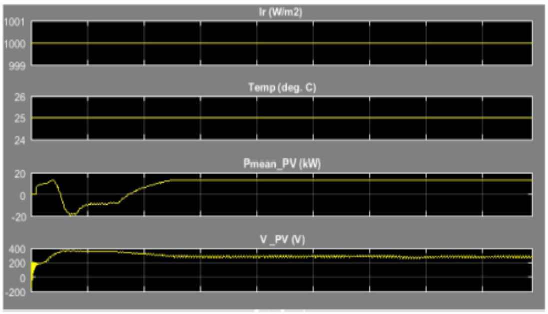

Fig. 15. Output power and PV voltage when irradiance = 1000 and temperature =25

IV. CONCLUSION

This paper presents interfacing of grid-connected PV system, identify its components, and describe how it works. The MPPT with perturb and observe (P&O) algorithm has extracted the maximum amount of power from the PV array with high efficiency in a dynamic response time. The three phase inverter was implemented successfully and its output was fed to a band pass filter and gave a clear sinusoidal alternative current, its power quality output meets the grid standard. The sinusoidal pulse width modulation technique used in the VSI was implemented properly and reduced the filtering requirements. The switching technique has used the PV system as a backup supply to the house when the grid is offline and provides protection to the utility workers in fault conditions, was implemented successfully. All simulation results, obtained under MA TLAB Simulink environment, show the control performance and dynamic behaviour of grid connected photovoltaic system provides good results and show that the control system is efficient.

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