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Design of two-stage soft-switched module inverter for photovoltaic applications

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In this paper two stage boost photovoltaic micro inverter system using maximum power point tracking is presented. First the photovoltaic module is analyzed using SIMULINK software. The main aim of the paper is the boost converter with microinverter to be used along with a Maximum Power Point Tracking control mechanism. The MPPT is responsible for extracting the maximum possible power from the photovoltaic and feed it to the load via the boost converter which is used to steps up the voltage to required magnitude. Both the boost converter, and the solar cell are modelledusing Sim Power System blocks. Here the voltage source inverter is cascaded and it injects sinusoidal current to the grid. The dynamic stiffness are obtained when load or solar insolation changing rapidly. This paper investigates in the detail concept of Maximum PowerPoint Tracking (MPPT) which significantly increases the efficiency of the solar photovoltaic system.

Keywords: *Boost converter, grid connected photovoltaic (PV) system, Voltage Source Inverter, Maximum Power Point Tracking (MPPT), PWM generator.*

1.0 INTRODUCTION

The present renewable energy development and use will trigger a fourth industrial revolution because of reducing costs of energy converter. Of all the renewable energy sources, photovoltaic power generation is a critical part of overall renewable energy development. According to the world energy organization predictions, as the traditional energy sources (such as coal, oil, etc) gradually dry up, renewable energy power generation will play a important role. Governments are greatly concerned about the development of renewable energy.

The amount of solar energy produced in India in 2007 was less than 1% of the total energy demand. The grid-connected solar power as of December 2010 was merely 10 MW[1]. Government-funded solar energy in India only accounted for approximately 6.4 MW of power as of 2005. However, India is ranked number one in terms of solar energy production per Watt installed, with an insolation of 1,700 to 1,900 kWh/kWp. 25.1 MW was added in 2010 and 468.3 MW in 2011. By end September 2014, the installed grid connected

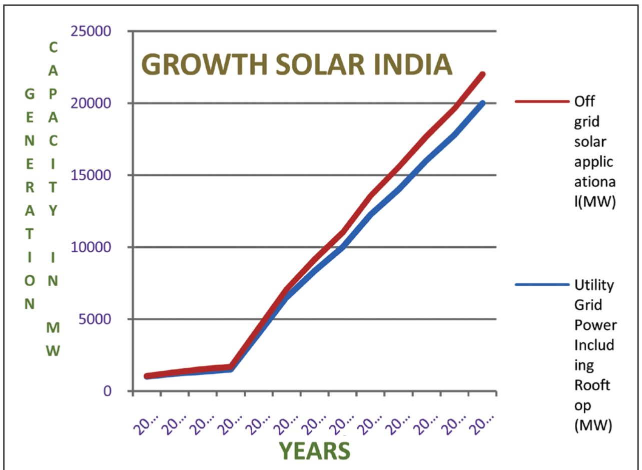

FIG. 1 GROWTH OF SOLAR IN INDIA

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solar power had increased to 2,766 MW, and India expects to install an additional 10,000 MW by 2017, and a total of 20,000 MW by 2022.

1.1 Solar Elements

Solar panels produce direct current at a voltage that depends on module design and lighting conditions. Modern modules using 6-inch cells typically contain 60 cells and produce a nominal 30 volts. For conversion into AC, panels are connected in series to form an array that is effectively a single large panel with a nominal rating of 300 to 600 VDC. The power then runs to an inverter, which converts it into standard AC voltage, typically 230VAC/50Hz for India.

Additionally, the efficiency of a panel's output is strongly affected by the load the inverter places on it. To maximize production, inverters use a technique called Maximum Power Point Tracking (MPPT) to ensure optimal energy harvest by adjusting the applied load. However, the same issues that cause output to vary from panel to panel affect the proper load that the MPPT system should apply. If a single panel operates at a different point, a string inverter can only see the overall change, and moves the MPPT point to match. This results in not just losses from the shadowed panel, but the other panels too. Shading of as little as 9% of the surface of an array can, in some circumstances, reduce system-wide power as much as 54%.

Another issue is that string inverters are available in a limited selection of power ratings. This means that a given array normally up-sizes the inverter to the next-largest model over the rating of the panel array. For instance, a 10-panel array of 2300 W might have to use a 2500 or even 3000 W inverter, paying for conversion capability it cannot use. This same issue makes it difficult to change array size over time, adding power when funds are available. If the customer originally purchased a 2500 W inverter for their 2300 W of panels, they cannot add even a single panel without over-driving the inverter Microinverters are small inverters rated to handle the output of a single panel, with recent modifications allowing one small microinverter to handle two panels, reducing overall cost. Modern grid-tie panels are normally rated between 220 and 245W, but rarely produce this in practice, so microinverters are typically rated between 190 and 220 W. Because it is operated at this lower power point, many design issues inherent to larger designs simply go away; the need for a large transformer is generally eliminated, large electrolytic capacitors can be replaced by more reliable thin-film capacitors, and cooling loads are reduced and hence fans are not required.

Microinverters produce grid-matching power directly at the back of the panel. Arrays of panels are connected in parallel to each other, and then to the grid. This has the major advantage that a single failing panel or inverter cannot take the entire string offline.

Microinverters have several advantages over conventional inverters. The main advantage is that small amounts of shading, debris or snow lines on any one solar module, or even a complete module failure, do not disproportionately reduce the output of the entire array. Each microinverter harvests optimum power by performing maximum power point tracking for its connected module.

2.0 SOLAR CELL DESIGN

A solar cell is basically a PN junction fabricated in a thin substrate of semiconductor. When exposed to sunlight, electron-hole pairs are created by photons that carry energy higher than the band-gap energy of the semiconductor. Figure 2 shows the equivalent circuit of PV Cell.

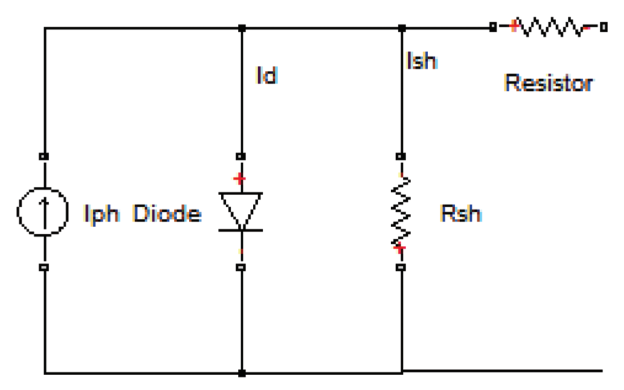

FIG. 2 PV CELL

The typical I-V output characteristics of a PV cell are given by the following equations:

Module Photo current (I_{ph}):

$$Iph = \frac{[I_{scr}+k_i(T-298)]G}{1000} \quad ....(1)$$

Module reverse saturation current (I_{rs}):

$$I_{rs} = I_{scr} \;/\; e^{(\frac{qVoc}{N_s}KAT)} - 1 \quad ....(2)$$

Module saturation current (I_0):

$$I_o = I_{rs} = [\frac{T}{T_r}]e^{\frac{qEgv}{BK(\frac{1}{T_r}-\frac{1}{T})}} \quad ....(3)$$

The current output of PV module (I_c) :

$$I_c = N_p I_{ph} - N I_o [e^{\frac{q(V_c+I_{ph})}{(NAKT)}} - 1] \quad ....(4)$$

Where,

V_c is output voltage of PV module (V)

T_r is the reference temperature = 289 K

T is the module operating temperature

A is an ideality factor = 1.6

K is Boltzmann constant = 1.3805 $\times 10^{-23}$ J/K

q is electron charge=1.602$\times 10^{-19}$ V

R_s is the series resistance of PV module Ω

I_{scr} is the PV module short circuit current = 1.1 A

K is the short circuit current temperature coefficient=0.0017 A/^{o}C

G is the PV module illumination = 1 kW/m^2

V_0 is the band gap for silicon = 1.1 eV

V is the open circuit voltage = 18 V

PV Simulink Diagram

PV array Simulink waveforms are shown in Figure 2 and 6.

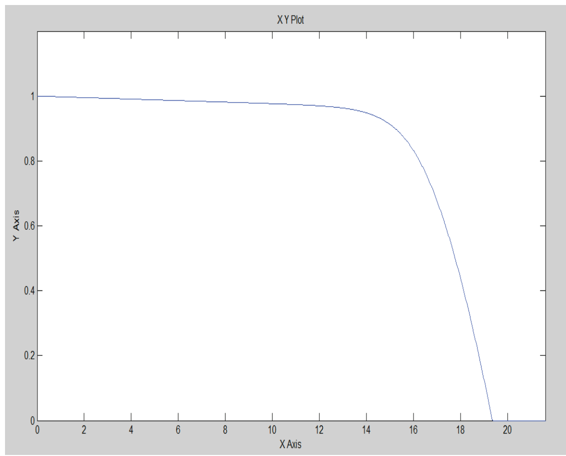

FIG. 3 V-I CHARACTERISTICS OF SOLAR CELL

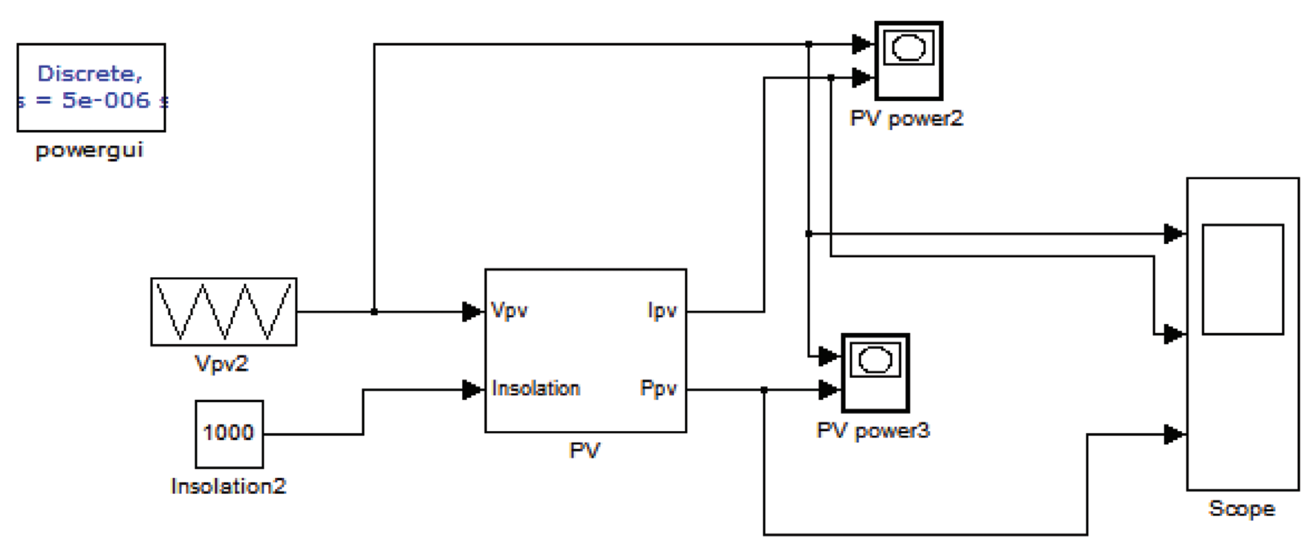

FIG. 4 PV ARRAY SIMULINK DIAGRAM

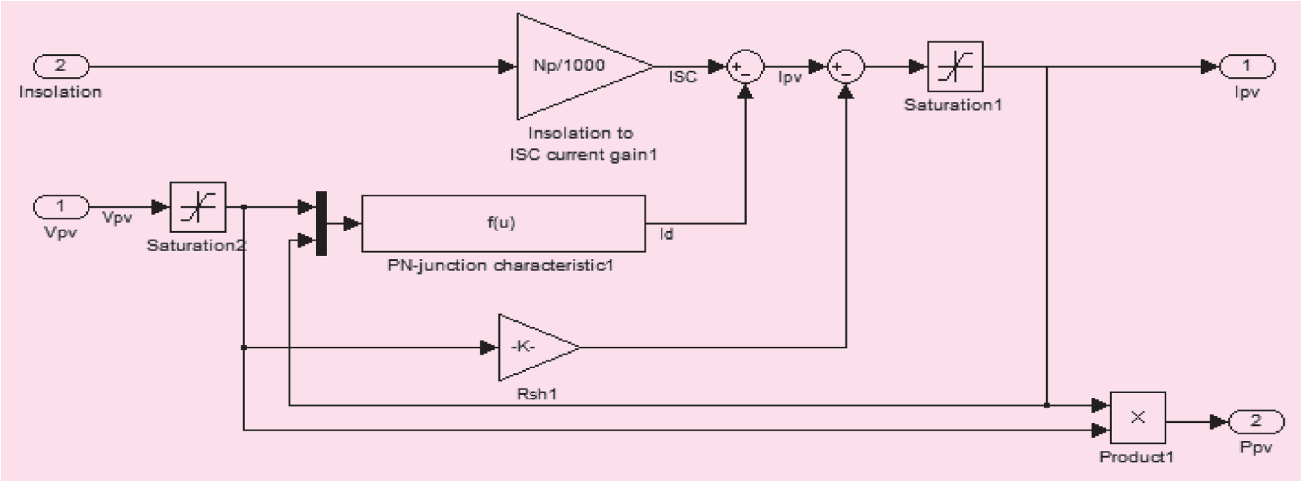

FIG. 5 SUBSYSTEM FOR PV

Simulation Diagram and subsystem of PV array is shown in Figure 4 and 5.

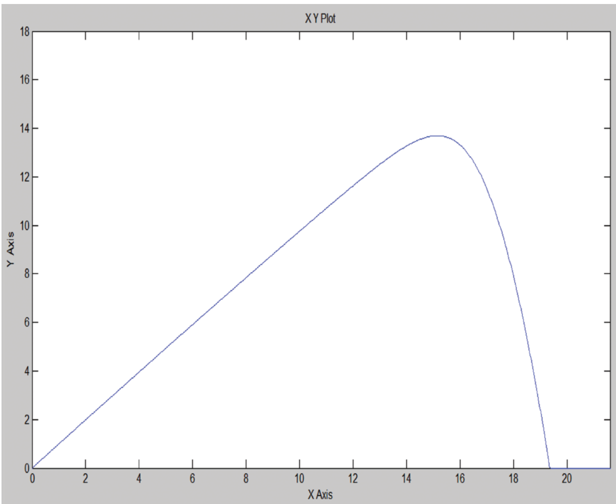

FIG. 6 P-V CHARACTERISTICS OF SOLAR PANEL

3.0 OVERVIEW OF DC-DC CONVERTER

DC-DC conversion technology is a major subject area in the field of power electronics power engineering and drives. This conversion technique is widely adopted in industrial application and computer hardware circuits. The simplest DC-DC conversion technology is a voltage divider, potentiometer and so on. But the effect of these simple conversion techniques resulted in poor efficiency due to fact that transfer output voltage is lower than the input voltage.There have been more than 500 prototypes of DC –DC converter developed for more than 60 years. All new topologies and presently existing DC-DC converters were designedto meet some sort of industrial or commercial applications. They are usually called by their function, for example, Buck converter, boost converter, buck-boost converter and Zero Current Switching [ZCS] and Zero Voltage Switching [ZVS] converters which are used to reduce, increase voltage respectively. DC-DC converters (e.g. Boost, buck, buck, boost, etc.)is also implemented with other devices as Maximum Power Point Trackers [MPPT] for photovoltaic module, for example, in a real time MPPT employing a DC-DC boost converter operating in conduction mode is used. It also includes a passive non dissipative turn ON turn OFF snubber in order to achieve high efficiency and to reduce EMI level due to soft switching.

3.1 Boost Converteranalysis

The designed DC-DC boost converter is connected between the photovoltaic module and the load so as to enable the module operates at maximum power at all time [2]. Boost converter is made up offour elements as shown below in Figure 7, they include the inductance, diode, capacitor and MOSFET. As the name of the converter implies, it steps up the input voltage which makes the output voltage greater than the input voltage. The converter is controlled through the MOSFET which acts as a switch. The ON and OFF of the switch (MOSFET) controls the output voltage by changing the voltage of the inductance so as to enable the photovoltaic module power the load at maximum voltage. The operation of the converter is analysed in different operating condition as continuous conduction mode, etc.Switching time measured from equation 5.

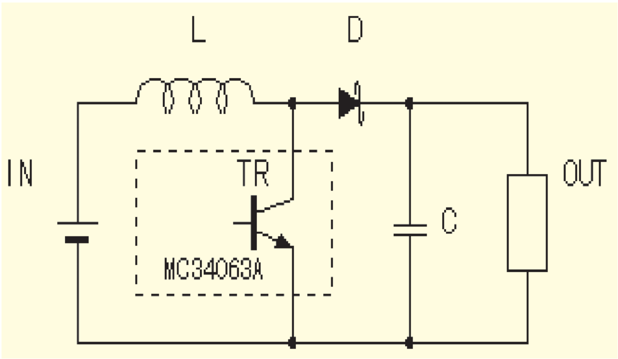

FIG. 7 BOOST CONVERETER CIRCUIT

$$\frac{\Delta I_1}{\Delta t} = \frac{V_i}{L} \quad ....(5)$$

At the end of the On-state, the increase of on state current is given by:

$$\Delta I_{1ON} = \frac{V_i \times D \times T}{L} \quad ....(6)$$

D is the duty cycle. It represents the fraction of the commutation period T during which the switch is ON. Therefore D ranges between 0 [TR is never on] and 1 [TR is always on]. During the Off-state, the switch TR is open, so the inductor current flows through the load. By considering there was zero voltage drops in the diode, and a capacitor is large enough for its voltage to remain constant, the derivation of load current is

$$V_i - V_o = L\frac{dI_1}{dt} \quad ....(7)$$

Therefore, the variation of I_1 During the Off-period is

$$\Delta I_{1off} = \frac{[[V_i - V_o][1-D]T]}{L} \quad ....(8)$$

As we consider that the converter operates in steady-state conditions, the amount of energy stored in each of its components has to be the same at the beginning and at the end of a commutation cycle. In particular, the energy stored in the inductor is given by,

$$E = \frac{1}{2} L \times I_1^2 \quad ....(9)$$

3.2 DC - DC Boost Converter Analysis

As stated above that DC-DC boost converter is used as photovoltaic interface and is designed to boost the output voltage to 24V to meet the requirement of the load [LED based light]. Therefore, the inductor current has to be the same at the beginning and the end of the commutation cycle. This can be written as

$$\Delta I_{1on} + \Delta I_{1off} = 0 \quad ....(10)$$

Substituting ΔI_L ON and ΔI_L OFF by their expressions yields:

$$\Delta I_{1on} + \Delta I_{1off} = [\frac{[V_i \times DxT]}{}] + \frac{[[V_i - V_o] \times [1-D] \times T]}{L} = 0 \quad ....(11)$$

This can be written as:

$$\frac{V_o}{V_i} = \frac{1}{[1-D]} \quad ....(12)$$

This in turns reveals the duty cycle to be (equation)

$$D = 1 - \frac{V_i}{V_o} \quad ....(13)$$

Equation 14 represents the boost converter, transfer function where

V_0 = output voltage,

V_i = input voltage and

D = duty cycle. Also

F_s = switching frequency,

L = boost inductance

C = represent output capacitance.

$$\frac{V_o}{V_i} = \frac{1}{1-D} \quad ....(14)$$

$$\Delta I = V_i \times \frac{D}{F_s} \times L \quad ....(15)$$

$$\Delta V = I_0 \times \frac{D}{F_s} \times C \quad ....(16)$$

$$P_i = P_o = V_i \times I_i = V_o \times I_o \quad ....(17)$$

4.0 INVERTERS

Thus, based on the inverter configuration differences, the grid-connected PV system can be classified into four groups: centralized type, string type, multi-string type, and module integrated type [3].

4.1 Centralized type

The centralized invertersare usually implemented on largescale PV farms and connect to interface a large number of PV panels to the grid. The PV panelsare connected in series firstly (or called strings) to generate a sufficiently high voltage and avoidfurther amplification, and then these series are connected in parallel through string diodes toobtain the desired high power level. This arrangement is the earliest configuration type as it offerseconomies of scale. Later on because of severe disadvantages, the usage of the centralizedinverters decreases.

4.2 String type

The string type has several PV panels which are connected in series as a string. Each string is connected to a DC/AC converter, which allows the MPP of each PV string to be optimized, and the expanding of a PV system could be simply realized by inserting additional strings and inverters to the existing platform. This type of inverter can be considered a reduced version of the centralized inverter. The voltage level can be high to avoid voltage amplification, or the voltage level can be lowered by involving a transformer or DC/DC converter to the inverters [4]. Therefore the number of PV panels is more flexible to construct each string.

4.3 Multi-string type

The multi-string type has several PV panels are connected in series and then connected with a low power DC/DC converter as a string, while several DC/DC converters as multiple strings are connected together with one DC/AC converter. The multi-string type can be referred to as a variation of two-stage inverter string type, which can also realize optimal MPP of each string and flexibility with string design [5-6]. The multi-string inverter combines the advantages of string inverter with the lower costs of centralized inverter. Although string type and multi-string type offer an improvement compared with centralized type, they still suffer from some disadvantages as high initial cost associated with acquisition and installation.

4.4 Module-integrated type

The module integrated type inverter is illustrated as in Figure 8 are also referred to as micro-inverters, and the power range is commonly between 150 W and 300 W. Each PV panel has a single inverter attached at the back. The output of micro-inverters are connected together to convert raw DC power from a PV panel to AC power and provide power into the grid, thus no high voltage DC cable is required as centralized type inverters. Since micro-inverters can perform a dedicate PV power harvest for every single PV panel, the misleading problems caused by shading, dust, dirt, or other possible non-uniform changes in temperatures and irradiations are minimized compared with other type of inverters. Moreover, micro-inverters have a low voltage DC link, thus when failure cases take place [7], it is easy to replace or repair the broken part, and during this process, little affect will happen on the whole power generation system.

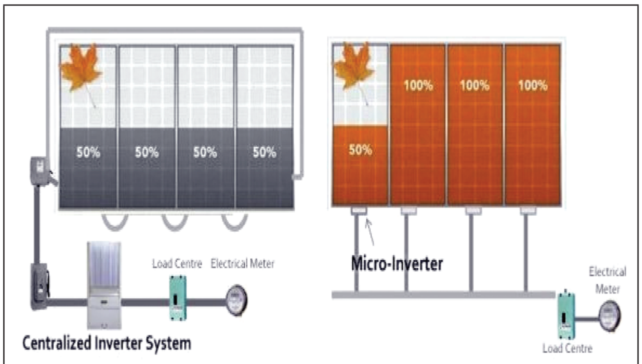

FIG. 8 MICRO INVERTER FED PV SYSTEM

These plug & play inverters are easily installed, simple in maintenance, and possible in mass production. Whereas they allow greater flexibility by allowing the use of panels with different specifications, different ratings, or produced by different manufacturer. This type of inverters would be the development trend of PV system design.

There are various inverter topologies suitable for micro-inverter applications. Based on different consideration reference, the inverter topologies could be classified into different groups [8-10]. For electrical ground consideration, the micro-inverter could be classified into galvanic isolation and non-galvanic isolation. Whereas based on the number of power processing stages, the micro-inverter could be classified into single-stage inverter, double-stage inverter, and three-stage inverter.

5.0 MAXIMUM POWER POINT TRACKER [MPPT]

A maximum power point tracker is a high-efficiency DC-DC converter, which functions as an optimal electrical load for photovoltaic cell, most commonly used for a solar panel or array and converts the power to a voltage or current level which is more suitable to whatever load the system is designed to drive [11-14]. have a power output of the cell. Maximum power point tracker (MPPT) is basically an electronic system that controls the duty cycle of the converter to enable the photovoltaic module operate at maximum operating power in all conditions and not some sort of mechanical tracking system that physically rotate the photovoltaic modules to face sunlight directly [15]. The advantages of MPPT regulators are greatest during cloudy or hazy days, cold weather or when the battery is deeply discharged. There are different types of maximum power point tracker methods developed over the years and they are listed below as follows Perturb and Observe method, Incremental conductance method, Artificial neutral network method, Fuzzy logic method, Peak power point method, Open circuit voltage method, and Temperature method etc [16]. from overall performance and reliability perturb and observe method is shown in Figure 9. The MPPT plays a very significant role because without the MPPT the desire output electrical power will not be achieved with changing weather conditions

5.1 Flow chart P&O

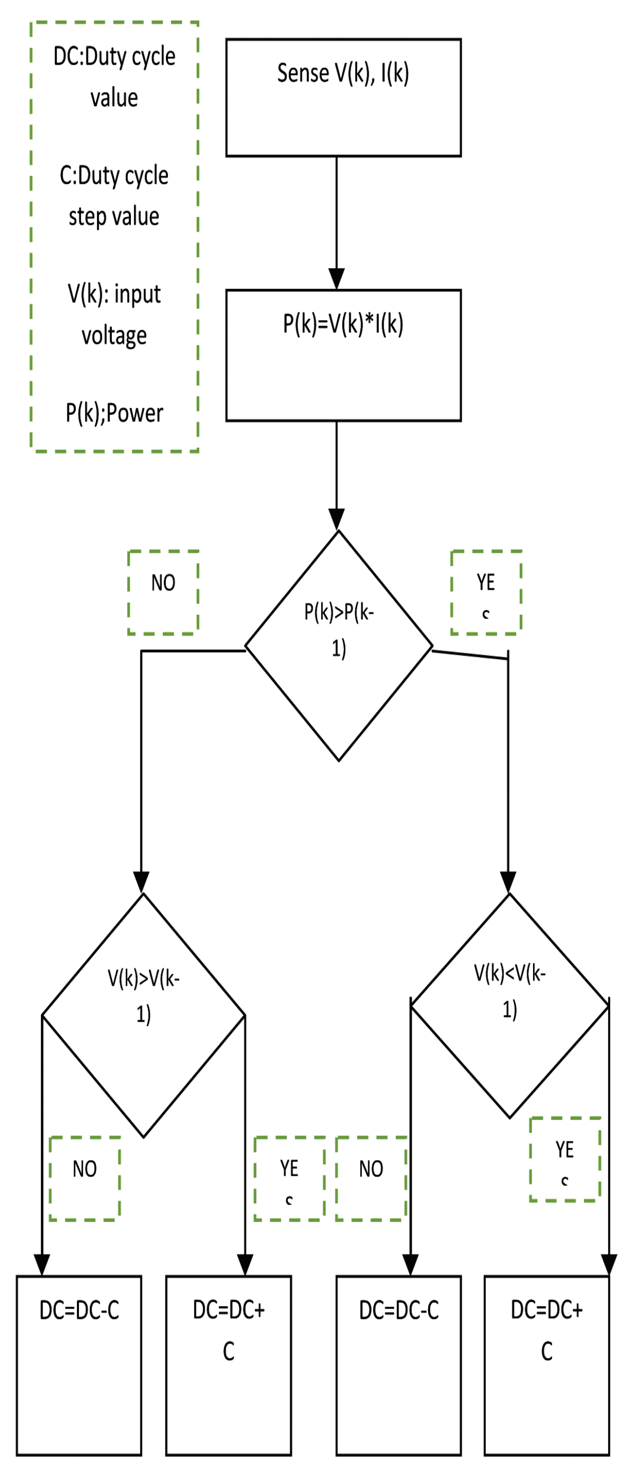

FIG. 9 P & O FLOW CHART

6.0 SIMULATION OF MICRO INVERTER

Simulation of micro inverter configured PV is done using MATLAB/SIMULINK™ .

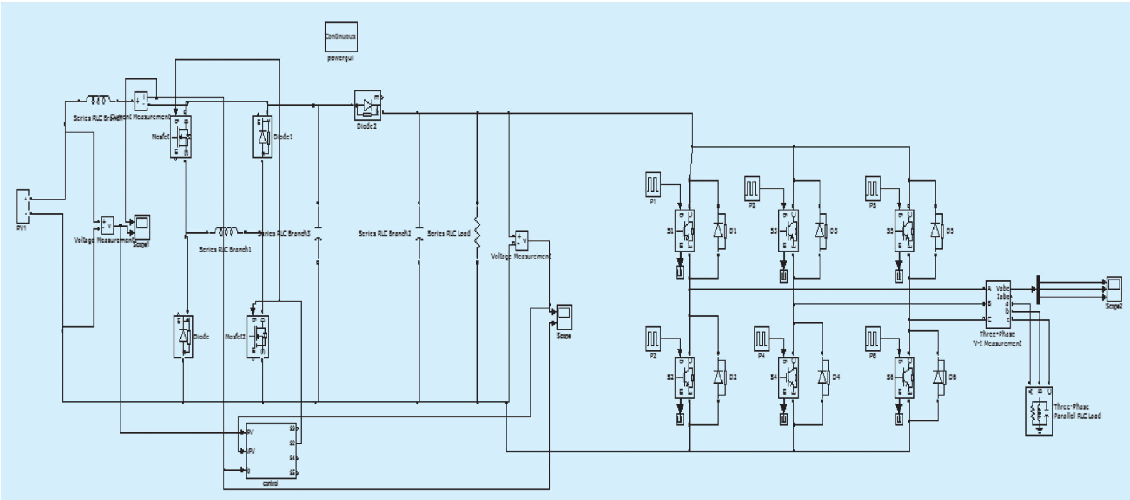

FIG. 10 MATLAB DIAGRAM FOR PV SYSTEM

Figure 10 shows an overall simulation diagram for micro inverter fed photovoltaic system. Figure 11 shows subsystem for the controller.

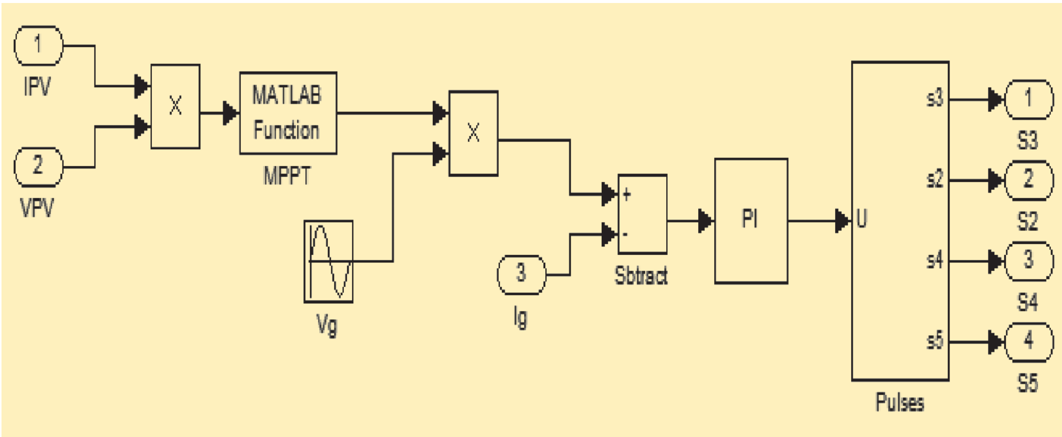

FIG. 11 CONTROLLER SUBSYSTEM

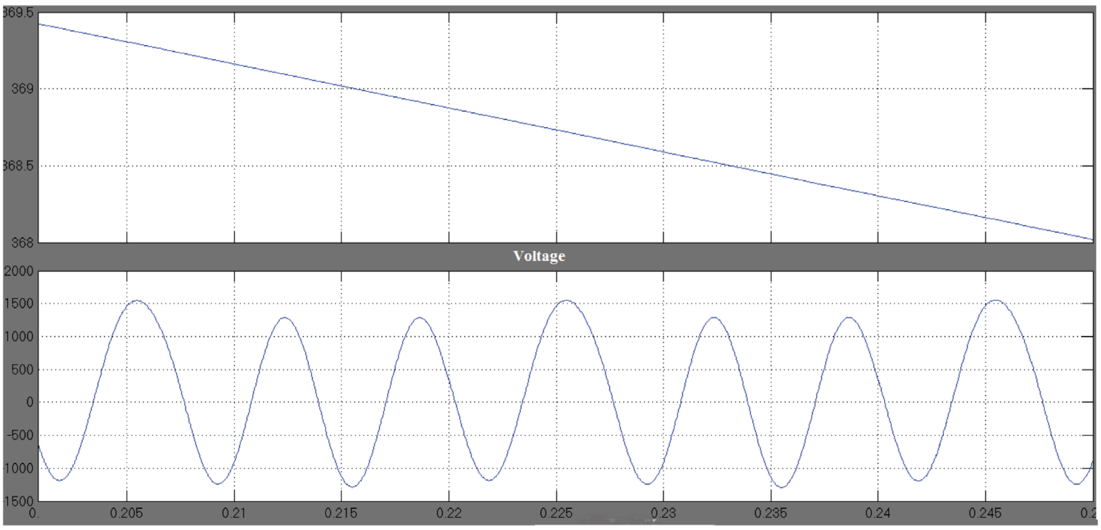

FIG. 12 CONVERTER OUTPUT WAVEFORMS

Figure 12 shows voltage and current waveforms of converter and PV system.

The following specifications are used in designing the PV micro inverter

- Input voltage of DC-DC converter 12.7 V
- Output voltage of DC-DC converter 300 V
- Power from PV panel is 4 kW

7.0 CONCLUSION

In this paper various types of grid connected inverter topologies have been presented, compared and analysed through a simulation study using SIMULINK™. The Photovoltaic powered micro inverter system is successfully designed, modelledand simulated using MATLAB SIMULINK™.

The main conclusions follow,

i. The proposed micro inverter efficiently raises the input voltage to the required level.

ii. It is also embedded with MPPT which is designed for harvesting maximum solar power from the PV module.

iii. Output of individual model can be measured and overall output is increased both healthy and partial shading conditions.

iv. Individual panel performance can be measured.

Appendix:

```
function A = mppt(a,p,v,flag,Lstep,Ai,step,decr)
% -----------------------------------------------------------------------
if a <= 0.01
     A = Ai;
     return
elseif flag==0
     if abs(v)>=0
          if p>=0
               A = Ai-step-abs(Lstep);
               return
          else
               A = Ai+step+abs(Lstep);
               return
          end
     elseif p>=0
          A = Ai+step+abs(Lstep)-(decr*0.4);
     else
          A = Ai-step-abs(Lstep);
     end
end
% -----------------------------------------------------------------------

function [Lstep]=Step_determination(a,p)
% -----------------------------------------------------------------------
if a>=45
     Lstep = 2;
elseif a>=25
     Lstep = 0.75;
elseif a>=15
     Lstep = 0.2;
elseif a>=2
     k = 0.5;
     Lstep = (p*k)/100;
else
     k = 0.25;
     Lstep = (p*k)/100;
end
% -----------------------------------------------------------------------

function A = pert(Vpv)
% -----------------------------------------------------------------------
step = 0.1;
flag = 0;
decr = 0;
Ai = 4;
Pi = 0;
Voc = 21.5*6;
Vi = 0.9*Voc;
Pe = Ai*Vpv;
delPe = Pe-Pi;
delV = Vpv-Vi;
a = abs(delPe);
Lstep = Step_determination(a,delPe);
A = mppt(a,delPe,delV,flag,Lstep,Ai,step,decr);
% -----------------------------------------------------------------------
```

FIG. 13 P&O MATLAB CODING

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