

Model of Grid Connected Photovoltaic System Using MATLAB/SIMULINK

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Abstract:- The energy sources like oil, coal and natural gas are depleting very quickly. Nuclear fission produces radioactive waste which is very harmful for human body. So we need alternative source like renewable energy sources for electric power generation. Energy from the sun is one of the promising options option for electricity generation as it is available everywhere. In this thesis Paper, the performance of a single phase Grid connected PV system is studied. The system includes PV module, a DC/DC converter, a DC/AC inverter and LCL filter . There are two control mechanism in the designed PV system where the first one is for maximum power point tracking of the PV module and another one is for injecting the desired amount of active and reactive power to the grid. The whole system is designed and simulated by MATLAB(simulink).

Keywords:- Photovoltaic, MPPT, Pulse width modulation, Perturbation and Observation, Active and Reactive power, Boost Converter, Anti-islanding.

1. Introduction

A Grid Connected solar PV system is a type of electrical inverter that convert direct current electricity from PV module into alternating current(AC). When the PV system is connected to the grid, it can transfer the extra energy to the grid after fulfilling the local demand. But when the system generates less than what is required to support the local demand, than extra energy is extracted from the grid. Thus PV solar energy acts as an alternative resource of electricity. The PV system, designed in this work, aims to transfer electrical power from PV panels to the grid [1] –[2]. First, a dc-dc Converter is used to boost up PV voltage to a level higher than the peak of grid voltage. The converter also tracks the

maximum power point of PV module. There are many algorithm for tracking maximum power point . In this system I used perturb and observe method. PV module's voltage and power need to sense for tracking maximum power point in this method [3]-[5]. Then, a pulse width modulation (PWM) based dc-ac inverter (voltage source inverter) is used for enforcing sinusoidal voltage waveform with matching phase frequency with grid voltage [6]-[9]. The output wave shape of PWM inverter is Pulse width modulated wave. Therefore, I used an LCL filter for coupling the inverter to the grid. It is one kind of low pass filter that converts this modulated wave to pure sine wave [10]. Finally I incorporated a control mechanism in order to supply the desired amount of real and reactive power to the grid from the PV system [11]-[12]. Active power is controlled by varying the angle between grid and inverter voltage. The supply of reactive power is controlled by varying the amplitude of inverter voltage.

Many of the previous strategies of grid connected PV system using simulink are described in a short view. But this paper present's a wide view of this system and propose some different techniques which are simple and give accurate result than any other method.

The structure of the work presented in this paper is organized in the following sequence: PV module's model technique is described in section 2, in section 3 Boost converter design law is described, MPPT is described in section 4, PWM based VSI inverter is described in section 5, in section 6 LCL filter design law is described, Active and reactive power control technique is described in section 7, Anti-islanding protection system design is presented in section 8, in section 9 measurement system is described , section 10 shows the

whole design model and section 11 described simulation results. Now, the basic model of Grid connected PV system is given below :-

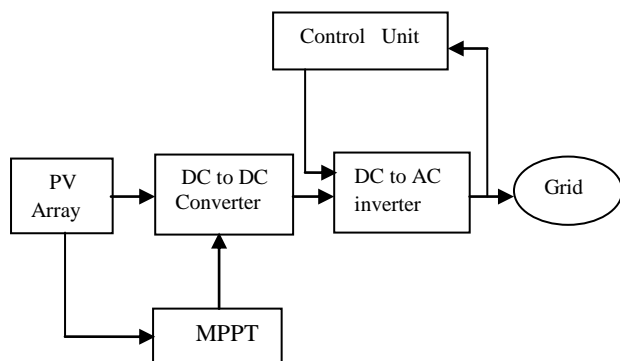


Fig. 1:- Basic structure of Grid connected PV system

2. Model of PV module

The basic structure of PV cell is given below :-

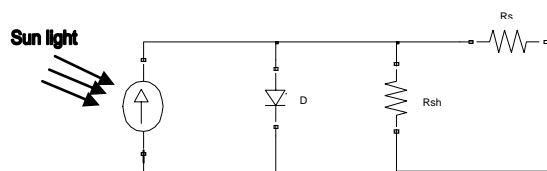


Fig. 2:- Basic model of PV cell

R_s = series resistance

R_{sh} = shunt resistance

$$\text{So, } I = I_L - I_o \left[e^{\left(\frac{q(V+R_s I)}{akT} \right)} - 1 \right] - \frac{V+R_s I}{R_{sh}} \quad (1)$$

Here, I = cell output current, I_o = cell reverse saturation current, α = diode ideality constant, I_L = light generated current .

$$\text{Open circuit voltage, } V_o = (kT/q) \ln[I_L/I_o] \quad (2)$$

A PV module has been modeled in MATLAB [13]-[14]. Open circuit voltage is 200V and short circuit current is 5A (In practical case, one PV module's rating is not so high. So that PV modules are connected in parallel or series to form a PV array for getting high power).The PV module is given :-

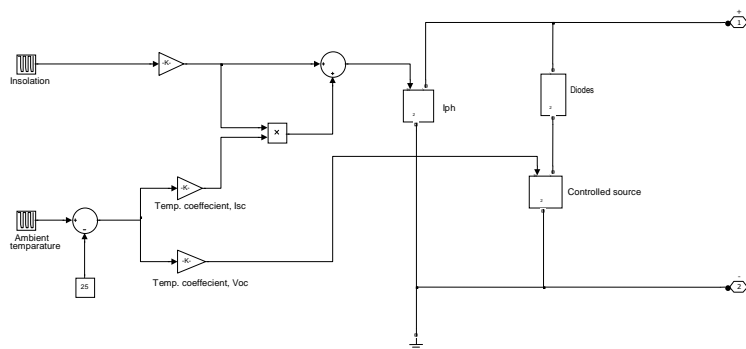


Fig. 3:- Model of PV module in MATLAB

Now, P-V characteristics of this PV module is given below :

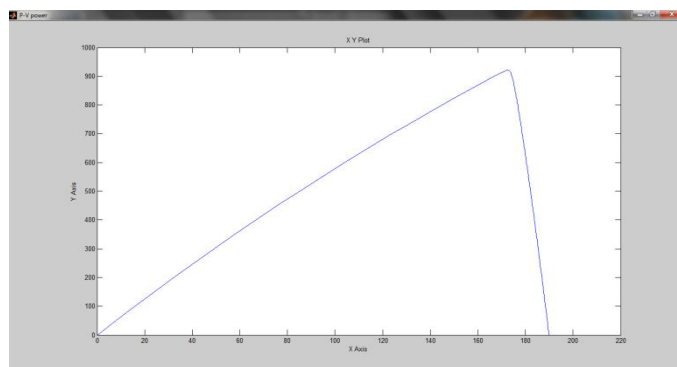


Fig. 4:- P-V characteristics curve at 30°C and 1000 W/m^2 of PV module

In general PV module characteristics is dependent on temperature and insolation. The module's current is affected by the insolation & little bit affected by temperature. On the other hand voltage is affected by temperature & little bit affected by insolation . That means ;

Temp.↑ , $V \downarrow$, little bit current ↑

Temp.↓ , $V \uparrow$, little bit current ↓

ins.(W/m^2)↑ , $I \uparrow$, little bit voltage ↑

ins.(W/m^2)↓ , $I \downarrow$, little bit voltage ↓

3. DC to DC Converter

In this section I used Boost converter. It is one of the DC to DC converter. Boost converter is used to 'step-up' a source voltage to a higher level. The gain from boost converter is directly proportional to the duty cycle (D). The equation is given below:-

$$\frac{V_o}{V_{in}} = \frac{1}{1-D} \quad (3)$$

When boost converter is in PV applications, the input voltage coming from PV panel is changed with atmospheric conditions. Therefore if the duty cycle vary than we get maximum power point of PV module.

The design law of Boost converter [15]-[16] is given below:-

$$\text{inductor, } L \geq \frac{V_{om} * D_m * (1-D_m)}{|\Delta i| * F_{sw}} \quad (4)$$

$$\text{input capacitor, } C_{in} \geq \frac{I_m * D_m^2}{0.02 * (1-D_m) * V_{inm} * F_{sw}} \quad (5)$$

$$\text{output capacitor, } C_{out} \geq \frac{I_m * D_m}{\Delta V * F_{sw}} \quad (6)$$

here, F_{sw} = switching frequency, ΔV = ripple voltage for capacitor, I_m = output current at maximum output power, D_m = duty cycle at maximum input power, Δi = ripple current for inductor, V_{inm} = input voltage at maximum power point, V_{om} = maximum of output voltage.

I designed a boost converter that can deliver maximum 1kW DC power. The MATALB[simulink] model of boost converter is given :-

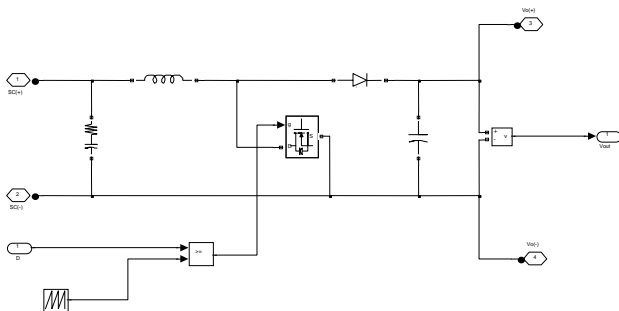


Fig. 5:- Boost converter

4. MPPT

MPPT means maximum power point tracking. The PV panel characteristics curve in fig. 4 , we see that there is a maximum power point. We want to operate PV module at this point. There are many algorithm for MPPT. I used Perturb & Observe(P&O) method. Though it fails to track the power under fast varying atmospheric conditions but it is still very popular and simple than any other method.

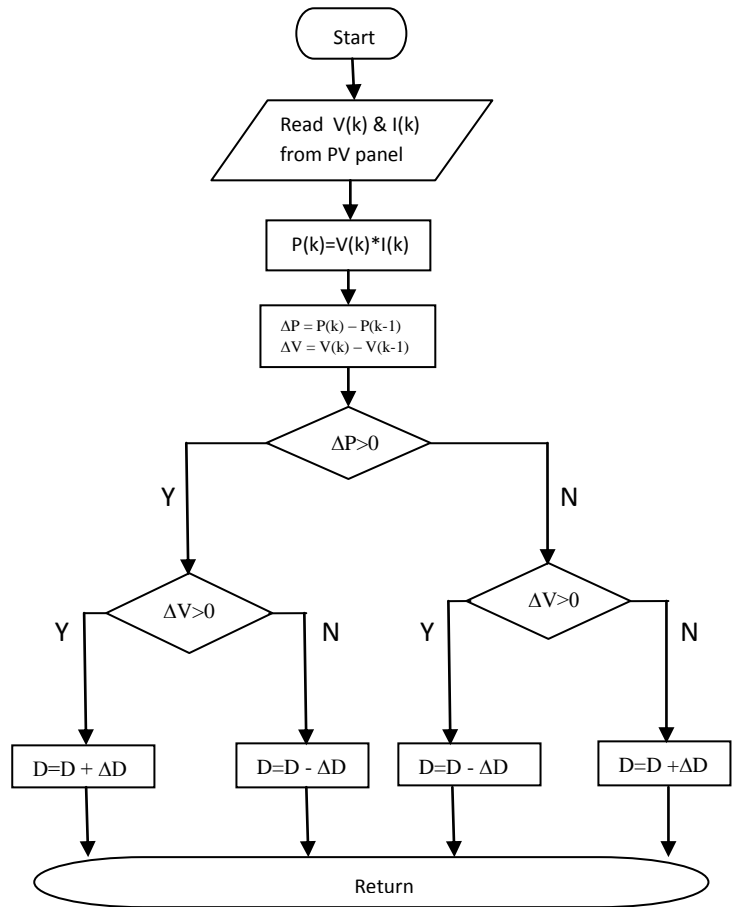


Fig. 6:- Flowchart of P&O algorithm

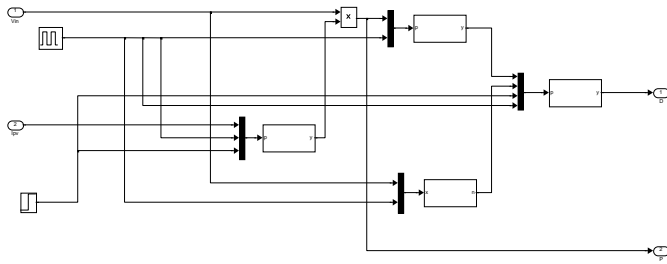


Fig. 7:- MPPT model in Simulink

It produces duty cycle which is dependent on PV module's voltage and power. Value of duty cycle is than compared to a high frequency saw tooth wave signal, show in fig. 5. So that the comparator produces a PWM signal that is fed to Mosfet in the dc to dc converter. The duty ratio of the PWM signal depends on the value of duty cycle. Furthermore the frequency of the PWM signal is the same as the frequency of the saw tooth waveform.

5. DC to AC Inverter

I used Unipolar based Voltage source PWM(pulse width modulation) dc to ac inverter. So that the shape of the output is Pulse width modulated wave. I used this because if we pass this type of signal in a low pass filter than we get pure sine wave which matches to the grid.

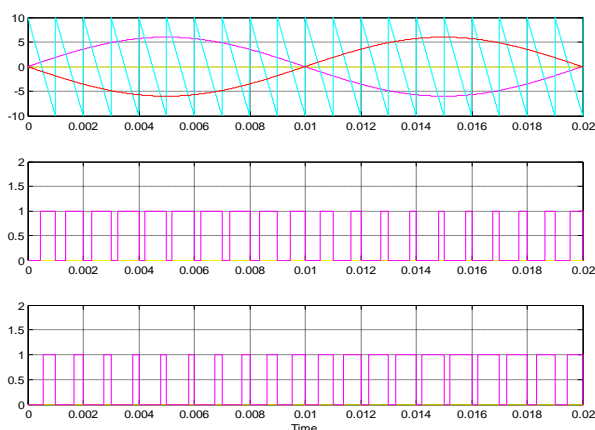


Fig. 8:- Waveforms of the Unipolar PWM

Here the sine wave is 50hz it is our reference signal which is compared to a high frequency saw tooth wave. So that the output shape of PWM inverter is given ;

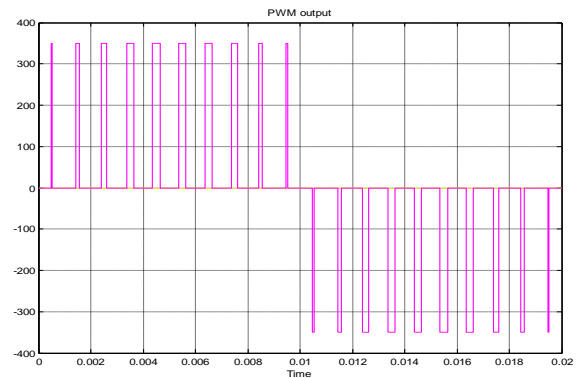


Fig. 9:- PWM Inverter Output

Due to the varying amplitude of the reference signal , the widths of the output pulses of PWM inverter is varied as well, resulting in pulse widths that are proportional to the amplitude of the reference signal wave. The PWM based voltage source dc to ac inverter in MTALAB[simulink] model is given;

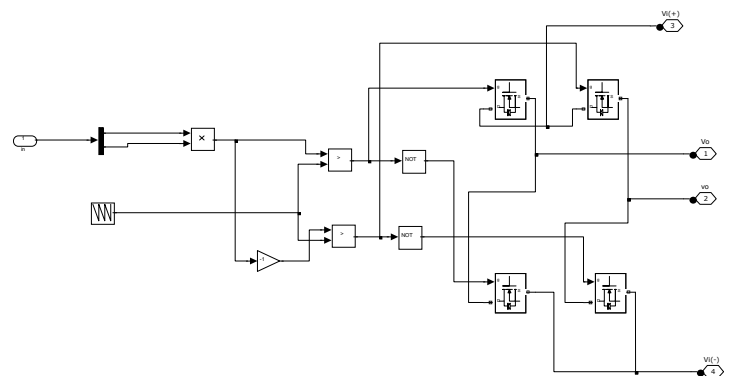


Fig. 10:- PWM based dc to ac inverter

Here, in PWM based inverter it is ensured that saw tooth signal's amplitude must greater than reference signal's amplitude. The reference signal is mainly grid signal because to operate initially in same phase with grid.

6. Filter

We can not connect this pulse width modulated signal to the grid. So that we need to use a low pass filter to convert this type of signal to pure sine wave. For connection to grid I used a L-C-L filter. Because the LCL filter has the advantage of providing a better decoupling between filter and grid impedance and a lower ripple current stress across the grid inductor. It is used at high power applications, in order to guarantee a stable power quality level. Furthermore, it provides better attenuation than other filters with the same size and by having an inductive output; it is capable of limiting current inrush problems. Now the design process [17]-[20] is given below :-

Resonance of LCL filter is,

$$f_{resonance} = \frac{1}{2\pi} \sqrt{\frac{(L+L_g)}{L*L_g*C_f}} \quad (7)$$

To avoid resonance, the resonance frequency should be;
 $10*f_n \leq f_{resonance} \leq 0.5*f_{sw}$

Now, inductance of this filter is; $L_T = L + L_g$ (8)

L_T should be chosen following this range ;

$$\frac{U_{dc}}{4\sqrt{3}*i_r*f_{sw}} \leq L_T \leq \frac{\sqrt{\frac{U_{dc}^2}{3}-E_m^2}}{2\pi*f_n*I_m} \quad (9)$$

$$L_g = \frac{E_n}{2\sqrt{6}*i_r*f_{sw}} \text{ and } L = L_g / 2$$

Choose C_f : to avoid a low power factor, in a general way, the reactive power that caused by filter capacitor C_f should be less than 5% of rated active power:

$$C_f < 5\% \frac{P_n}{3*2\pi*f_n*E_n^2} \quad (10)$$

Here, i_r = peak value of harmonic current, f_n = grid frequency, f_{sw} = switching frequency of PWM inverter, U_{dc} = DC voltage of converter, E_n = RMS value of grid voltage, E_m = peak value of grid voltage, P_n = active power of the system, I_m = peak value of current.

The Basic model of LCL filter is given below;

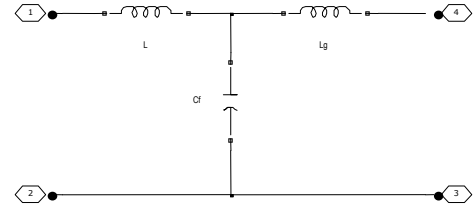


Fig. 11:- LCL Filter

The MATLAB model of LCL filter is given below :-

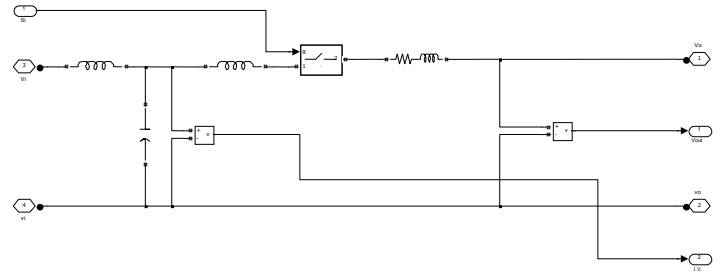


Fig. 12:- Filter

In figure-12 I used a circuit breaker (C.B.) for protection.

7. Control Unit

In this section the Control unit control's active & reactive power. Now to control power the phase diagram is given :-

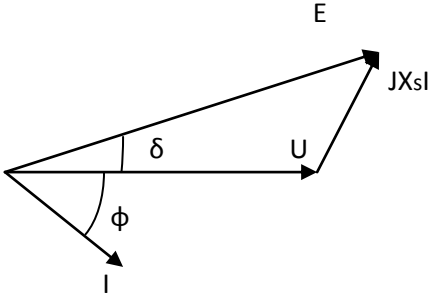


Fig. 13:- Phase diagram with grid voltage(U) and load angle(δ)

Here E is represented as inverter voltage , δ as load angle between the grid voltage and inverter voltage and φ as power angle between grid voltage and inverter current.

Now, the active power (P) provided by the inverter to the grid can be expressed as:

$$P = UI \cos(\delta) = \frac{UE}{X_s} \sin(\delta) \quad (11)$$

And reactive power (Q) provided by the inverter to grid can be expressed as:

$$Q = \frac{UE}{X_s} \cos(\delta) - \frac{U^2}{X_s} = \frac{U}{X_s} (E \cos(\delta) - U) \quad (12)$$

From (11) & (12) equation's the reactive and active power depend on the inverter output voltage magnitude E and load angle δ [12]. So , the active power injected into the grid can be controlled by the phase difference between inverter voltage and grid voltage. At the same time the reactive power can be controlled by the inverter output voltage magnitude E. Now, initially grid and inverter voltage are in same phase.

After a certain time if we lead inverter voltage, we can feed active power to grid. In fig.14 we see D = desire reference reactive power.

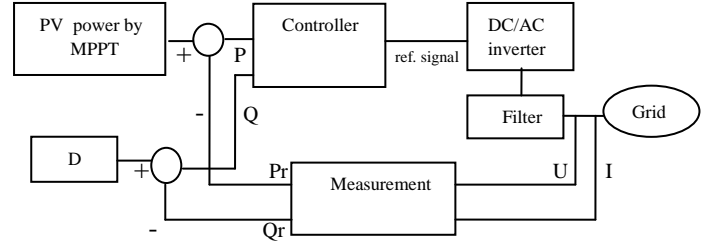


Fig.14:- Basic Diagram for controlling of Active & Reactive power

We also see that the error reactive and active power is reduced by the controller. The controller gives ref. signal and the value of amplitude and angle is varied until error is reduced. Reactive power and active power are directly proportional to the reference signal's amplitude(a) and phase angle(Θ). Because if ref. signal's amplitude is varied than inverter output voltage is also varied and if ref. signal's angle is varied than the phase difference between inverter voltage and grid voltage is also varied. In fig.14 the controller consists of mainly PI controller. Now for feeding active power to grid, the basic diagram of ref. signal's phase shifter is given:-

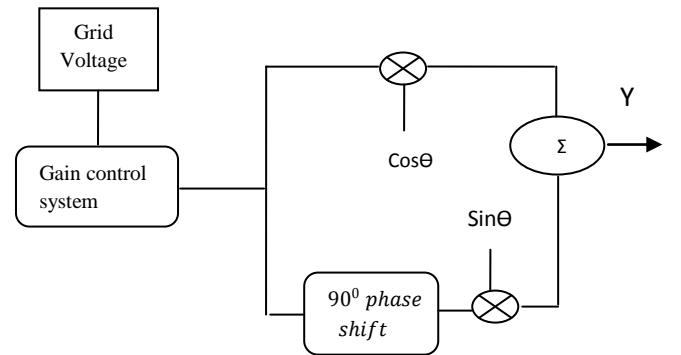


Fig.15:- Basic model of Phase shifter

$$Y = \sin(\omega t + \Theta) = \sin\omega t \cdot \cos\Theta + \sin\Theta \cdot \cos\omega t \quad (13)$$

Here the output of gain control system is always 2V P-P sine wave whatever the grid voltage is. By phase changing we can get power factor which is almost unity. The MATLAB[Simulink] model of Phase shifter is given:-

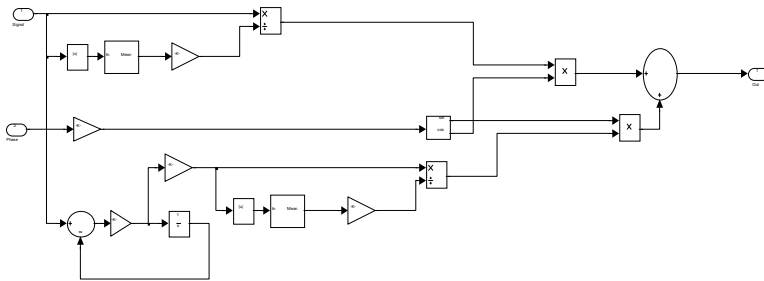


Fig.16 :- Phase shifter

The MATLAB[Simulink] model of Control Unit is given:-

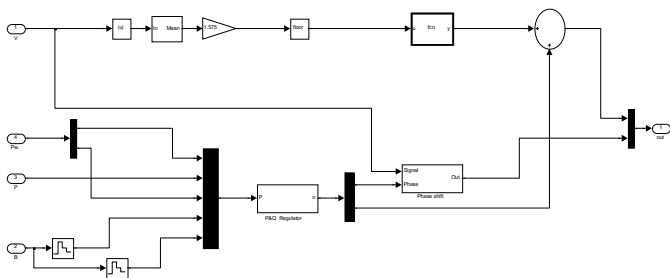


Fig. 17:- control Unit

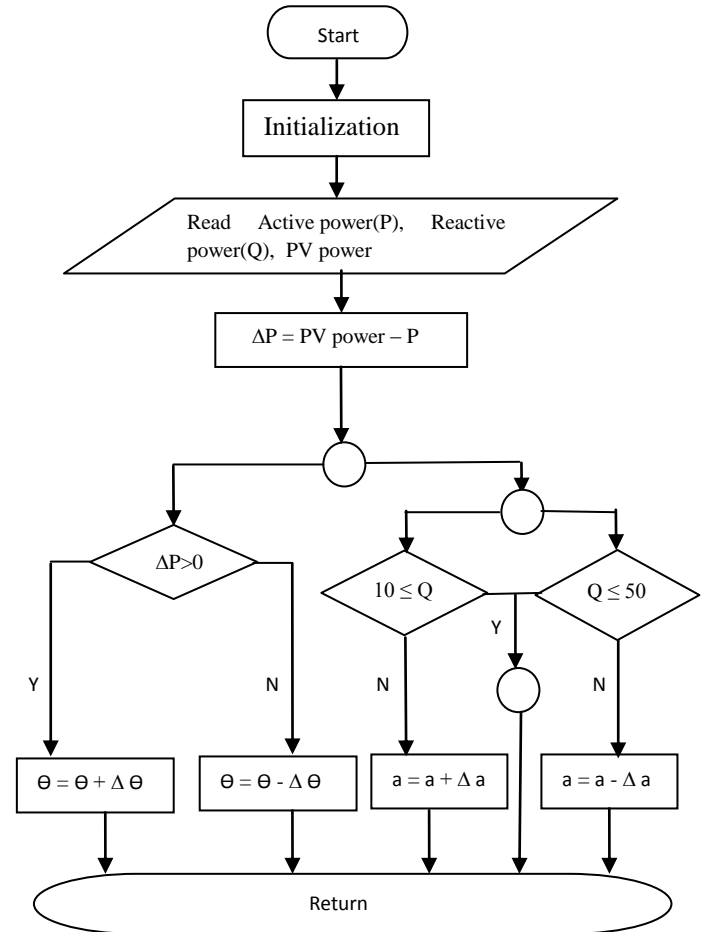


Fig. 18 :- flowchart of control unit algorithm

Here, from flowchart we see that, reactive power always lays between from 10 to 50 var.

8. Protection unit :-

Grid-tie inverters are designed to shut down automatically upon loss of utility supply, for safety reasons. They do not provide backup power during utility outages. So that, protection unit observe the islanding situation, when the utility supply fails. In case of islanding, the PV generators should be disconnected from mains. PV generators can continue to meet only the local load, if the PV output matches the load. If the grid is reconnected during islanding, transient over currents can flow through the PV system inverters and protective equipment such as circuit breakers may be damaged [21]. Now for anti islanding protection, grid voltage and frequency should be measured because the voltage or the frequency is changed during the grid failure. Now in the Protection Unit, frequency measurement process is given below ;

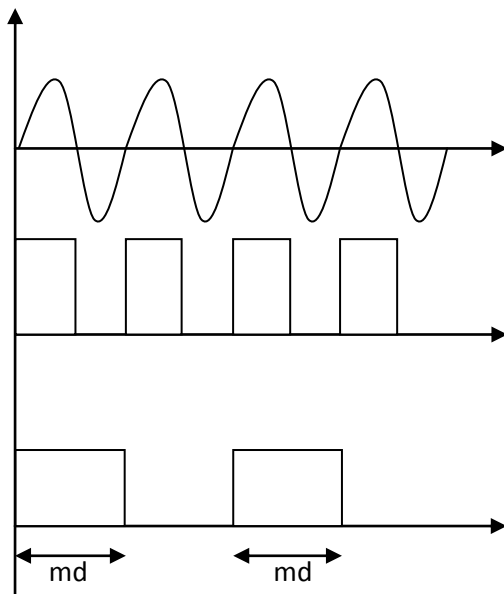


Fig. 19:- frequency measurement process

Here, md= measure duration(T). So that we can get the frequency of the grid signal by $f = 1/T$.

Now, to find out the peak value of voltage by MATLAB the procedure diagram is given below :-

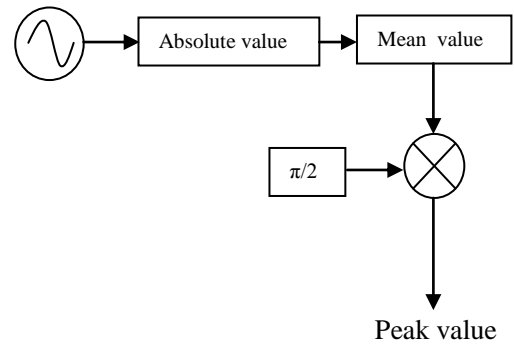


Fig. 20:- Voltage measurement process

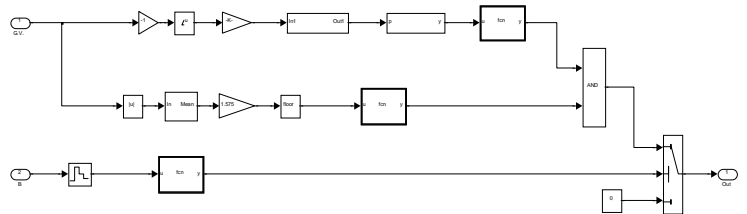


Fig. 21 :- Protection Unit

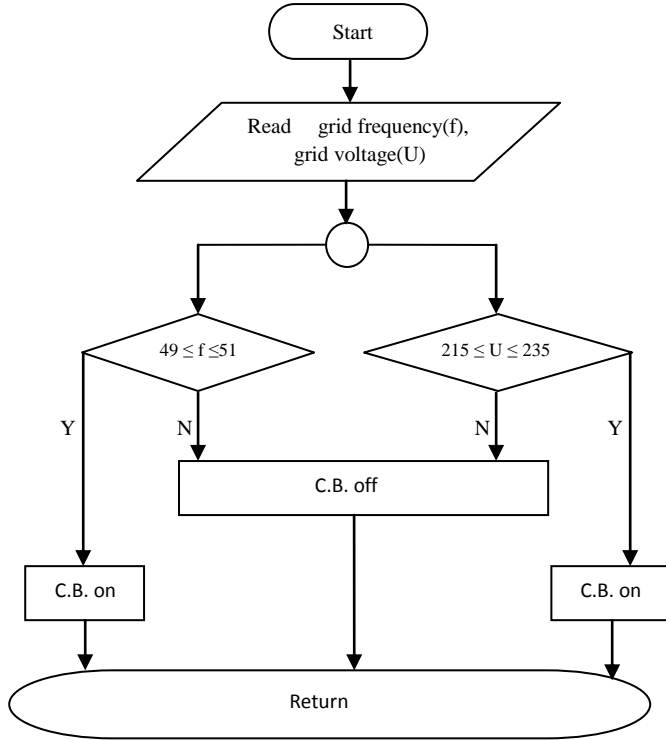


Fig. 22 :- flowchart of Protection unit algorithm

9. Measurement System

In the measurement system it measure's active(P) and reactive(Q) power associated with a periodic voltage-current pair that can contain harmonics. P and Q are calculated by averaging the V*I product with a running average over one cycle of the fundamental frequency, so that the powers are evaluated at fundamental frequency. So,

$$P = \frac{1}{T} \int_{t-T}^t V_{rms} * I_{rms} * \cos\theta dt$$

$$= \frac{1}{T} \int_{t-T}^t 0.5 * V_p * I_p * \cos\theta dt \quad (14)$$

$$Q = \frac{1}{T} \int_{t-T}^t V_{rms} * I_{rms} * \sin\theta dt$$

$$= \frac{1}{T} \int_{t-T}^t 0.5 * V_p * I_p * \sin\theta dt \quad (15)$$

Where, $T = 1 / f$ (fundamental frequency)

Now to find out angle between voltage and current the procedure diagram is given in fig 23. Same as for current. This diagram performs a Fourier analysis of the input signal of one cycle of the fundamental frequency [22]. We see that at output we get the complex form. Here n is harmonic. Now at first we find out inverse tangent of angle for both voltage and current from complex form. If we subtract the angle of current from angle of voltage we get the angle(θ) between voltage and current. If we find the magnitude value from both current and voltage complex forms we get the peak value of voltage and current. So after that follow the equation (16) & (17) we get active and reactive power.

$$P = 0.5 * V_p * I_p * \cos\theta \quad (16)$$

$$Q = 0.5 * V_p * I_p * \sin\theta \quad (17)$$

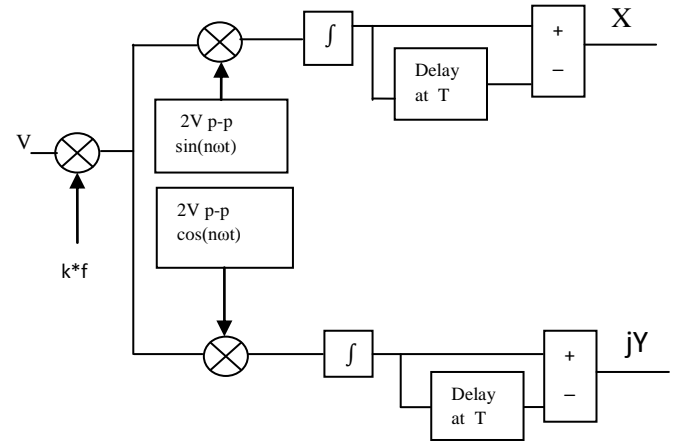


Fig. 23:- Complex form of voltage

The MATLAB[Simulink] model of measurement system is given below:-

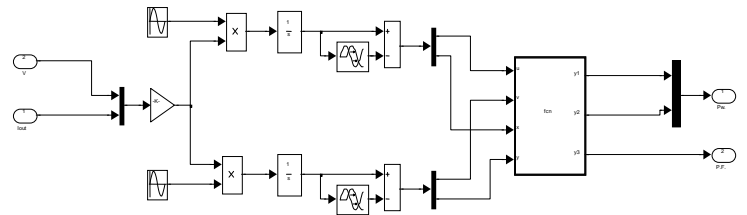


Fig. 24- Measurement system

I designed this measurement system that not only measure's active and reactive powers but also measure's power factor. The active and reactive power line is feedback signal for control unit and power factor line for observation. Here, $n = 1$ (1st harmonic) and gain, $k=2$.

10. Total Model

A Capacitor is used Between Boost converter & PWM inverter. This is the energy stored capacitor. It provides energy storage necessary to balance instantaneous power $Pac(t)$ delivered to the grid [23]. So that;

$$\begin{aligned} Pac - Pac(t) &= Pac - Pac (1 - \cos 2\omega t) \\ &= Pac \cos 2\omega t \end{aligned} \quad (18)$$

Here, Pac = average power delivery from PV module to grid

Now, $Pac > Pac(t)$, when capacitor is charged up and $Pac < Pac(t)$, when capacitor is discharged

Now, energy supplied to the during the time when $Pac > Pac(t)$, i.e. when the capacitor is charged from V_{DCmin} to V_{DCmax} .

$$\begin{aligned} \Delta E &= \int_{-T_{ac}/8}^{T_{ac}/8} Pac \cos 2\omega t \, dt \\ &= \frac{Pac}{2\omega} \int_{-\pi/2}^{\pi/2} \cos \theta \, d\theta = \frac{Pac}{\omega} \end{aligned} \quad (19)$$

This energy must match the change in energy stored on the capacitor:-

$$\begin{aligned} \Delta E &= \frac{1}{2} C V_{DC \max}^2 - \frac{1}{2} C V_{DC \min}^2 \\ &= C (V_{DC \max} - V_{DC \min}) \frac{V_{DC \max} + V_{DC \min}}{2} \\ &= C V_{DC} \Delta V_{DC} \end{aligned} \quad (20)$$

So from equation 19 and 20 we get,

$$\begin{aligned} C V_{DC} \Delta V_{DC} &= \frac{Pac}{\omega} \\ \text{So, } C &= \frac{Pac}{2\pi f * V_{DC} * \Delta V_{DC}} \end{aligned} \quad (21)$$

So that we get the value of capacitor.

Here, f = grid frequency

V_{DC} = DC-AC inverter input voltage

ΔV_{DC} = ripple voltage depend on capacitor

The whole design model of Single phase grid connected PV inverter in MATLAB[simulink] is given ;

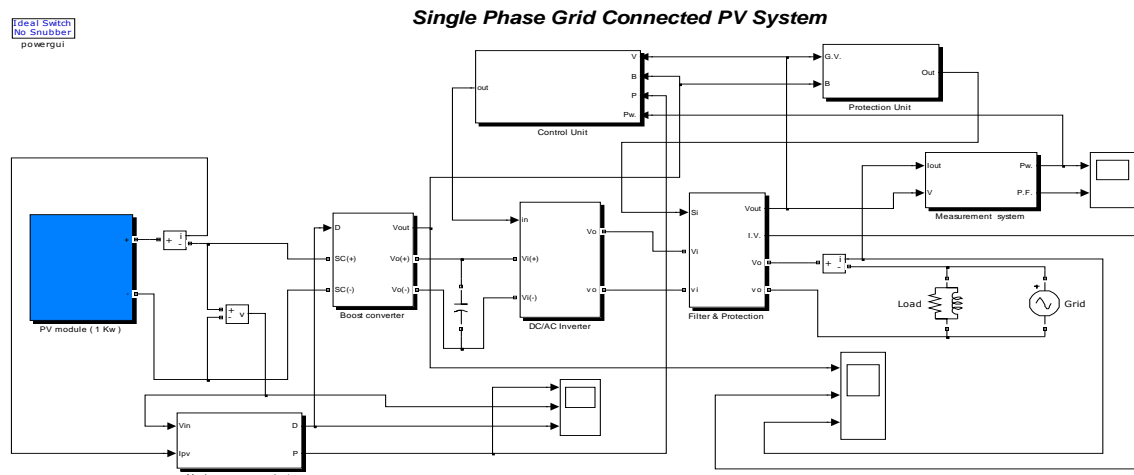


Fig. 25:- Single phase grid connected PV System

11. Simulation Results

The total simulation time is about 1.4sec. At 0.7sec PV module's voltage and current are changed. 3 scopes are used for observation. One is observed PV voltage, PV power and duty cycle for mppt. Another is observed Boost output voltage, Inverter output voltage and current. And last scope is observed Active and Reactive power, Power factor of the system .

a) Output of the PV system and duty cycle:-

In fig.26, we see that at 0.7s the V_{PV} and P_{PV} are decreased and duty cycle is increased. The value of duty cycle is varied depend on how PV power and voltage are changed.

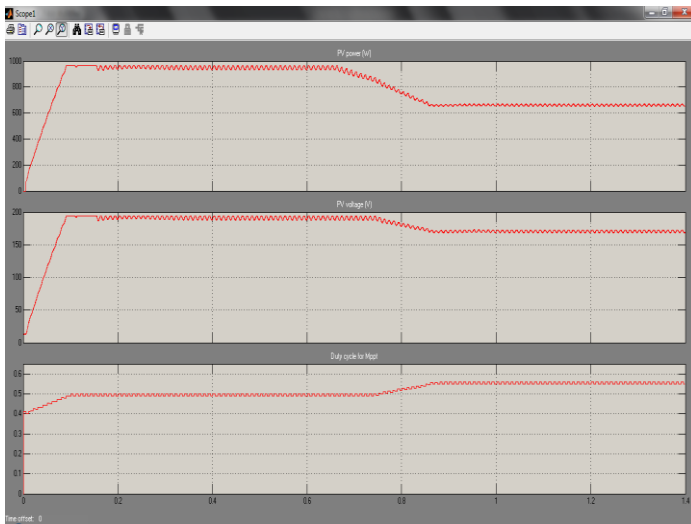


Fig. 26:- P_{PV} , V_{PV} and duty cycle

From fig.26 we see propose control technique operates the PV panel to the maximum power point and track it very fast. This Simulation result is accurate and so much similar to the previously worked [3]-[5].

b) Output wave shape of Boost and Inverter :-

Fig. 27 shows that inverter current flows at 0.1s. Because circuit breaker is on at that time.

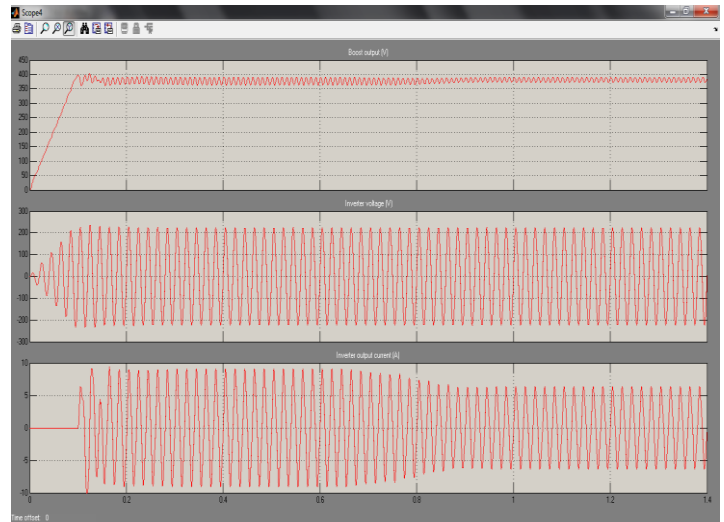


Fig. 27:-Boost output voltage and inverter output voltage & current

In this simulation, We see that at 0.7s that inverter output current is decreased because of PV power is decreased.

c) Result of Active and Reactive power & power factor :-

Fig. 28 shows that reactive & active power and power factor . At the first picture in fig. 28(Active and Reactive power) the black line represent's active power and red line represent's reactive power. At 0.7s Active power is decreased because of PV power is decreased.

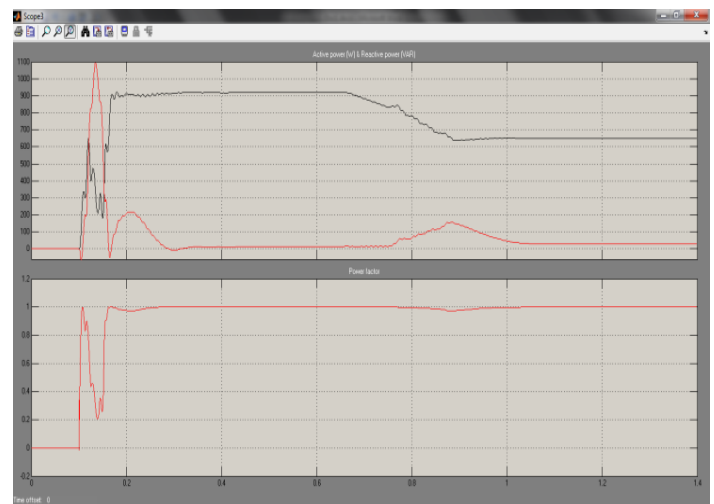


Fig. 28:- Active & Reactive power and Power factor

Here, Efficiency (The ratio of active power to the PV power) of this system is approximately 98% which is little bit higher than previous worked [11]. The power factor is also almost unity. So, overall this simulation result is satisfactory.

12. Conclusion

In this Paper single phase grid connected PV System has been analyzed. A practical case developed in MATLAB[simulink] simulation platform has been presented and the results confirm the adequate performance of whole designed control. Control laws are provided active & reactive power control and guarantees the maximum power point of PV module. Besides control laws can be easily implemented by means of microcontroller, operational amplifiers, analog multipliers in an experimental platform.

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