Research Article

Modeling and Simulation of a SAPV System

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Abstract

In this paper, photovoltaic's (PV) cell has been modeled and simulated under MATLAB/SIMULINK[R] platform. Proper power electronics interface and its control has been developed to match the load requirements corresponding to the characteristics of the studied PV array. As the PV modules exhibit non-linear characteristics, extraction of the maximum power from it is of very much importance to increase the overall utilization of the PV capacity. Therefore, in the present work, method of perturbation and observation has been used to track the maximum power point of a solar-array under different illumination intensity and panel temperature. Also, the feasibility of photovoltaic system has been demonstrated in standalone mode.

Keywords: Photovoltaic, Maximum power point, Perturbation and observation.

Notation

I_{ph} = amount of solar radiation received at the surface of solar cell.
I_d = the diode current.
I_{rp} = current through shunted resistance.
R_p = shunted resistance.
R_s = series resistance.
R_l = load resistance.

Introduction

Due to rapidly diminishing conventional sources of energy and large variations in their cost, there is a current and global need for renewable sources of energy. The various alternatives of renewable sources are biomass, wind, water, geothermal, tidal and solar power. Amongst the various alternatives available, solar energy is the more practical solution to the current requirement of energy due to its plentiful availability. PV panels are green power technology systems and exploit renewable solar energy facilitating towards a sustainable energy mix. They can meet our basic energy needs domestically, commercially, at the community level or even at a larger scale.

At present, the photovoltaic generation has gained acceptance worldwide, and there are many research works carried out in this field (M. G. Villalva *et al*, 2009).The P-V and V-I characteristics of a solar panel are obtained by varying temperature and radiation (C. Carrero *et al*, 2007; E..Matagne *et al*, 2007). Since these characteristic curves are non linear, various MPPT algorithms has been proposed in many literature works (D. P. Hohm *et al*, 2002; Panda Aurobinda *et al*, 2011;L. Fangrui et al, 2008;

Liu X *et al*, 2004 ;Go Seok-Il *et al*, 2011;.K.Husein *et al*, 1995) so as to track the MPP at different temperature conditions. P & O method has been used in this paper work, due to its simplicity and economic viability.

The PV generation can be broadly divided into islanded generation system and grid-connected generation system. A grid-connected PV system supplies electricity directly to the grid whereas stand-alone photovoltaic (SAPV) systems are independent of the utility grid. These types of systems may work independently or may be used in conjunction with a diesel generator or a wind turbine.

Around 8.4% of the PV systems installed in the world are in SAPV mode (Y.Thiaux *et al*, 2010). There are few aspects- like reliability and cost, which must be taken into account when working with SAPV system for the generation of electricity. SAPV are economically viable and very attractive option, especially when the connection of PV generator to the utility network is not available. Hence, SAPV system are useful for remote locations and household applications. In this paper, SAPV system is used for remote locations. The boost converter, three phase inverter and voltage regulator are used together to feed the load.

To demonstrate the feasibility of SAPV system, the power injected from PV panel is divided into following stages:

I. In the first stage, the PV panel is connected to the DC-DC converter (Mohan *et al*, 2003; Taufik, 2004) to increase the DC voltage level of the PV panel. Here, MPPT controller is also used to set the PV operating point at MPP.

II. In the second stage, DC power is converted into AC power through an inverter (B.K .Bose,2003; K.Rudion, 2007; D.N.Gaonkar *et al*, 2006).

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III. Finally, the AC power is fed to load.

This topology is used in MATLAB/SIMULINK environment.

Modeling and Simulation of PV Module

Fig.(1) represents the equivalent circuit model (M. G. Villalva *et al*, 2009) of a simple solar cell :
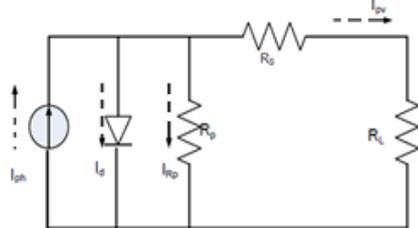

Fig.1 Equivalent circuit of photovoltaic cell

where,
I_{ph} is the amount of solar radiation received at the surface of solar cell.
I_d is the diode current.
I_{rp} is the current through shunted resistance.
R_p is the shunted resistance.
R_s is the series resistance.
R_l is the load resistance.

Applying KCL in Fig.1 , we get

$$I_{ph} = I_d + I_{rp} + I_{pv} \qquad (1)$$

The above equation can be rewritten as:

$$I_{pv} = I_{ph} - I_d - I_{Rp} \qquad (2)$$

$$I_{pv} = I_{ph} - I_0[exp\left(\frac{V_{pv}+I_{pv}R_S}{aV_t}\right) - \frac{V_{pv}+I_{pv}R_S}{R_S}] \qquad (3)$$

where, $V_t = \frac{N_S kT}{q}$,is the thermal voltage of the array, N_S is the no. of cells connected in series, k is the Boltzmann constant, T is the temperature in Kelvin and q is the charge of electron. Cells connected in parallel increase the current and cells connected in series provide greater output voltages. Equation(3) is used to plot the *I-V* curve seen in Fig. 2, which depicts three important points : short circuit (0, Isc), maximum power point (Vmp, Imp) and open-circuit (Voc, 0).
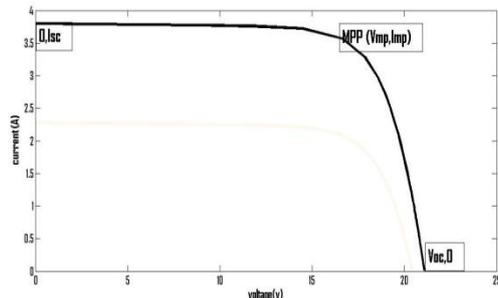

Fig.2 I-V characteristics of a practical photovoltaic device

A single diode model has been proposed in this paper work as it offers a compromise between simplicity and accuracy (C. Carrero *et al*,2007). Equation (4) depicts the linear dependence of photovoltaic current on solar irradiance and temperature .(E..Matagne *et al*,2007).

$$I_{ph} = \frac{G}{Gn}[I_{ph,n} + K_i(T - T_n) \qquad (4)$$

where, $I_{ph,n}$ is the photo generated current, G_n is irradiation and T_n is the temperature of array at reference condition (25ºC ,1000w/m^2).

The relation between diode saturation current *Io*, and temperature may be expressed as:

$$I_0 = I_{0,n}\left(\frac{T}{T_n}\right)^3 exp[\frac{q}{ak}E_g\left(\frac{1}{Tn} - \frac{1}{T}\right) \qquad (5)$$

where $I_{0,n}$ is the reference diode saturation current and is expressed as:

$$I_{o,n} = \frac{I_{sc,n}}{exp\left(\frac{V_{oc,n}}{aV_t}\right) - 1} \qquad (6)$$

where

$V_{oc,n}$ is the nominal open circuit voltage , $I_{sc,n}$ is nominal short circuit current and $V_{t,n}$ is the nominal thermal voltage of solar cell.
To match the open circuit voltage with the experimental data for wide range of temperature, equation (5) can be modified as

$$I_o = \frac{I_{sc,n} + K_1\Delta T}{exp[(V_{oc,n} + K_v\Delta T)/aV_t] - 1} \qquad (7)$$

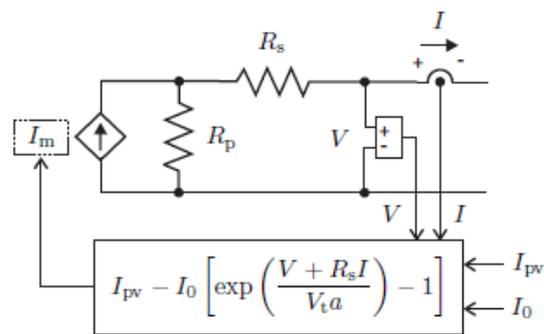The value of the module current , I_m can be calculated by the computational block shown in Fig. 3.

Fig. 3 PV array model circuit and equation of module current

$$I_m = I_{pv} - I_0[exp\left(\frac{V+R_SI}{V_t a}\right) - 1] \qquad (8)$$

Now, the equations (3), (7) and (8) are used to simulate the PV model in MATLAB/SIMULINK^R environment using the parameters of MSX60 solar array at nominal operating conditions as mentioned in data sheet supplied by the manufacturer.

Table 1: Parameters of the MSX60 PV array at 25 °C, 1000W/m^2.

Parameters	Values
I_{mp}	7.61A
V_{mp}	26.3V
P_{max}	200.143W
I_{sc}	8.21A
V_{oc}	32.9V
K_v	−0.1230V/K
K_i	0.0032A/K
N_s	54

Practical PV Array

A practical PV array consists of number of PV modules in series and parallel, as shown in Fig. 4.
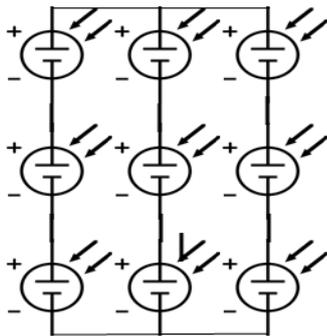

Fig.4 Solar PV array

To design a PV array with improved rating, equation (3) can be modified and written for an array as:

$$I_{pv} = N_p I_{ph} - N_p I_o \left[exp \frac{V_{pv} + IR_s \left(\frac{Ns}{Np} \right)}{aV_t N_s} - 1 \right] - \left(V_{pv} + IR_s \left(\frac{Ns}{Np} \right) \right) / R_p \left(\frac{N_S}{Np} \right) \qquad (9)$$

The peak power of the PV generator is obtained from the equation,

$$P_{pv} = \frac{E_L}{\eta_v \eta_R P_{SH}} S_f \qquad (10)$$

where,

E_L: Energy consumption per day
η_v : Inverter efficiency
η_R : Charge controller efficiency .
P_{SH} : The peak sun hours
S_f : The safety factor .

The number of necessary PV modules is obtained as:

$$NO._{PV} = \frac{P_{PV}}{P_{mpp}} \qquad (11)$$

If the voltage of the PV generator =280V, so number of modules in series is obtained as:

$$NO._{PVS} = \frac{V_{PV}}{V_{mpp}} \qquad (12)$$

And, number of such modules in parallel is given as:

$$NO._{STR.} = \frac{NO._{PV}}{NO._{PVS}} \qquad (13)$$

Thus , using above equations, a solar array can be designed

Maximum Power Point Tracking

The PV array has non-linear characteristics, hence, it is required to calculate the maximum power point (MPP) under varying environmental conditions. Also, when a PV array is directly connected to load, the impedance of the load dictates its operating conditions and hence it yields very low power. thus, a PV array needs to be oversized to compensate for a low power yield during winter months or cloudy days. This mismatch between a PV module output and a load may result in further over-sizing of the PV array and thus increases the overall system cost. To mitigate this problem, a maximum power point tracker (MPPT) can be used to maintain the PV module's operating point at the MPP. A MPPT algorithm is necessary to increase the efficiency of the solar panel. MPPTs can extract more than 95% of the PV power when properly optimized. Several MPPT techniques that have been used are works (D. P. Hohm *et al*, 2002; Panda Aurobinda *et al*, 2011;L. Fangrui et al,2008; Liu X et al,2004 ;Go Seok-Il *et al*, 2011;.K.Husein *et al*, 1995) :

- Constant Voltage (CV) method
- Open Voltage (OV) Method
- Incremental Conductance (IC) Methods
- Perturb and Observe (P&O) Methods
- Three Point Weight Comparison
- Fuzzy Logic Method
- Sliding Mode Method
- Artificial Neural Network Method

This paper deals with the P&O method for MPPT, due to its simplicity of implementation and other economic reasons.

- *Perturb and observe method*

This method is based on the principle of regularly perturbing the voltage and the current of PV by increasing or decreasing the duty cycle of boost converter and then measuring the power. The power output is measured and compared with the previous value in order to decide the next perturbation. Finally, a small perturbation (Δ*D*), is added to the original output voltage and the corresponding power is compared with the original one. If at any instant, the output power and voltage is greater than the previous computed power and voltage, then the direction of perturbation is maintained, otherwise it is reversed Panda (Aurobinda *et al*, 2011;L. Fangrui *et al*,2008). The flow chart of algorithm has 4 cases (Go Seok-Il *et al*,2011;.K.Husein *et al*,1995) as shown in Fig.5.
- When *ΔP <0 & V(n)>V(n-1),* this yields

$D (n+1) = D (n) – \Delta D$
- When *ΔP <0 & V(n)<V(n-1)*, this yields
  $D (n+1) = D (n) + \Delta D$
- When *ΔP >0 & V(n)<V(n-1)*, this yields
  $D (n+1) = D (n) - \Delta D$
- When *ΔP >0 & V(n)<V(n-1)*, this yields
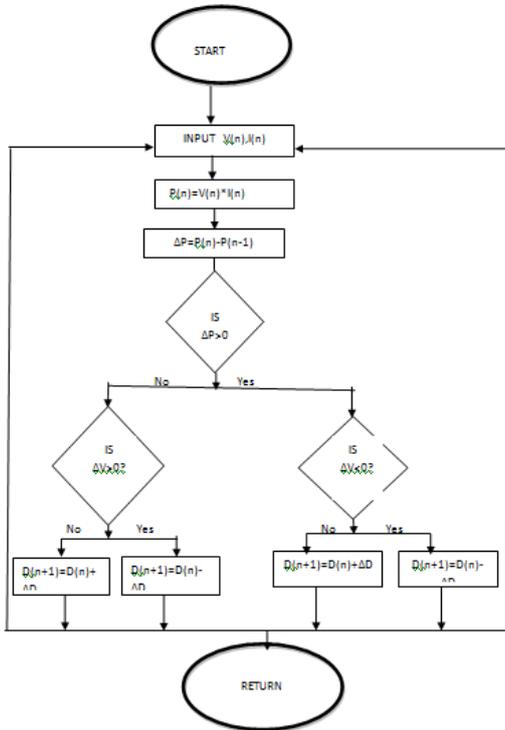 $D (n+1) = D (n) + \Delta D$

Fig. 5 Flowchart for P&O algorithm

The system uses a boost converter as shown in Fig. 6, in order to enhance the efficiency of solar panel. With the help of boost converter, the initially low voltage output is stepped up to a higher level. Although the use of the converter tends to introduce switching losses, yet is more viable and economic, when it comes to increase in efficiency.
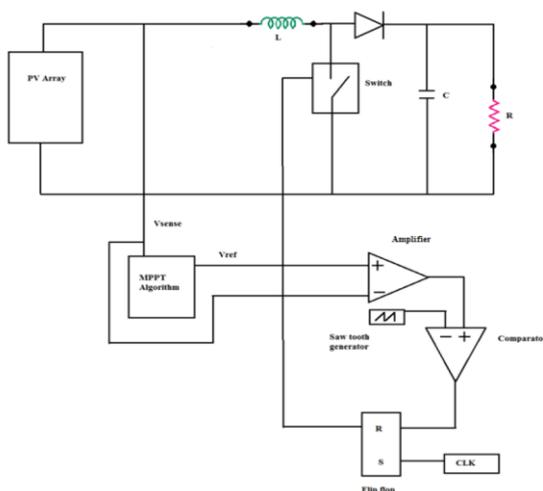
Fig. 6 Implementation of boost converter for MPPT system

Modeling of SAPV System

In a SAPV system, the PV array output is directly connected to the load. It is important to confirm that SAPV are economically viable, especially in remote locations.

In this paper, various components that make up this system as well as, their design and simulation models has been discussed.

Components of a SAPV System

- #### PV generator

A PV generator is a sustainable energy source, which comprises a solar cell, solar module or an array. Solar photovoltaic's has now emerged as one of the most important renewable energy source in terms of globally installed capacity. In the present paper, the focus is only on cell/module/array and its modeling has been discussed in Section 2 .

- #### Three phase voltage source inverter

Voltage source inverters (VSI) are mainly used to convert a constant DC voltage into 3-phase AC voltages with variable magnitude and frequency. Fig.7 shows a schematic diagram of a 3 phase VSI Taufik,2004; B.K.Bose,2003). The inverter is composed of six switches, S1- S6 . Two switches in each phase are used to construct one leg. The DC output of the PV array serves as an input to the inverter.AC output voltage from the inverter is obtained by controlling the semiconductor switches ON and OFF to generate the desired output.
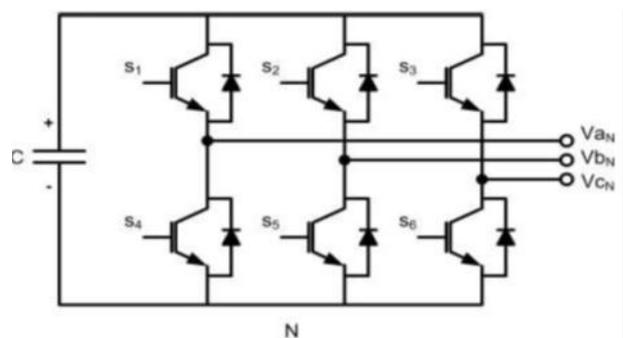

Fig.7 Three phase VSI

- #### LC filter

LC filter is used at the output of inverter.It allows for generation of sinusoidal voltages with lowTHD (K.Rudion, 2007; D.N.Gaonkar *et al*, 2006).They gain importance in applications where a high quality voltage is needed. Such applications include distributed generation (SAPV ,grid connected) and uninterruptible power supplies (UPS) to achieve a good output voltage regulation.

In this paper, second order LC-filter filter has been used. The corner frequency of the LC filter has to be chosen to filter the PWM switching ripples of the inverter

and pass the fundamental frequency component without attenuation (D.N.Gaonkar *et al*, 2006).
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• *Voltage Regulator*

The non-linear characteristics of a PV generator causes sudden voltage drop thereby resulting in instability and reduced efficiency of the system. Hence, the regulation of photovoltaic voltage to follow a time variant set point (V_{MPP}) is achieved through voltage regulator. The reliability and efficiency of a solar panel very much depends on the functioning of voltage regulator.

In this work, a PI regulator has been applied, which uses abc to dq and dq to abc transformations (D.N.Gaonkar *et al*, 2006). .The output of the PI regulator consists of three modulating signals. These signals are then fed to the PWM generator ,where they are compared with reference signals. As a result, gate pulses are generated and fed to the inverter switches.
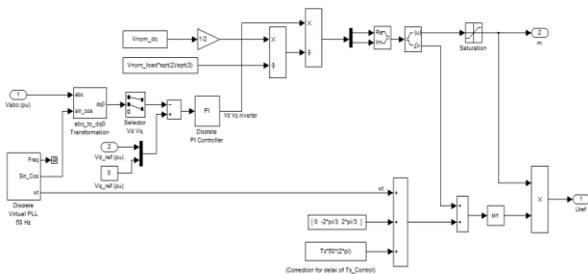
Fig.8 Simulink model of voltage regulator

System Modelling in MATLAB/SIMULINK

Fig. 9 shows the masked simulink structure of PV array based on eqn (1) to eqn (7). The model uses the solar irradiation (*G*), temperature (*T*), number of cell connected in series (*Ns*) and parallel (*Np*) and PV Voltage as input and generate the PV current as output as shown in Fig. 9.
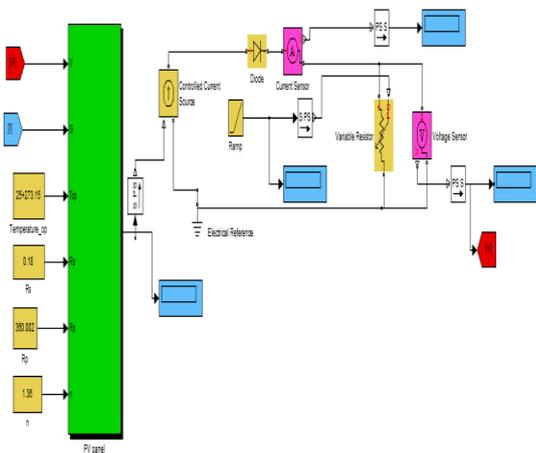
Fig. 9 Simulink model of the solar PV panel

The PV characteristics obtained by varying the solar insolation but keeping temperatures constant which are fed into the PV panel model have been plotted as shown in Fig.10.
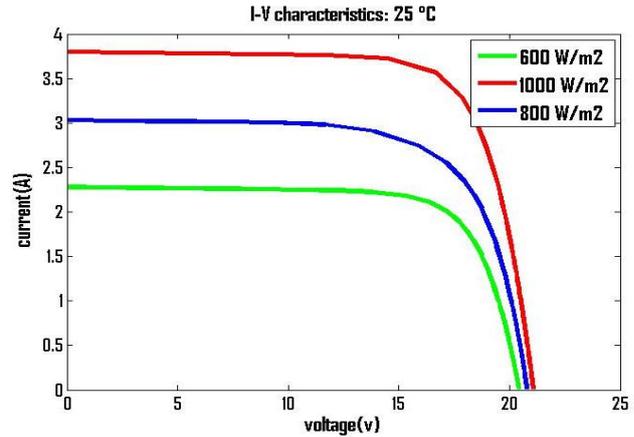
Fig.10 I-V characteristics with different irradiation at constant temperature

From Fig.10, it is observed that by decreasing the solar irradiation at constant temperature, the open circuit current of the PV array also decreases.
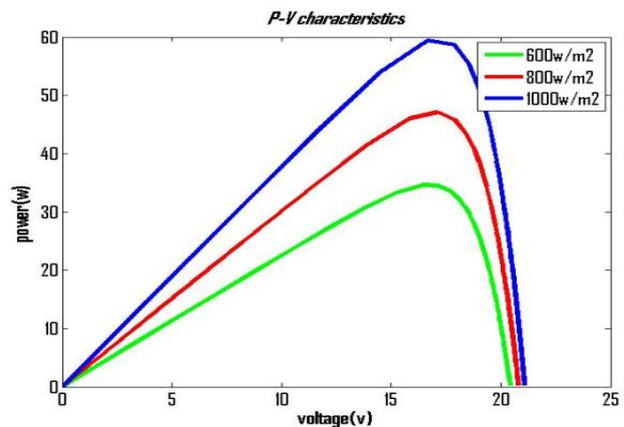
Fig.11 P-V Characteristics with different irradiation at constant temperature

From Fig.11, it is observed that with increase in solar radiation at constant temperature, the power output of PV array also increases.
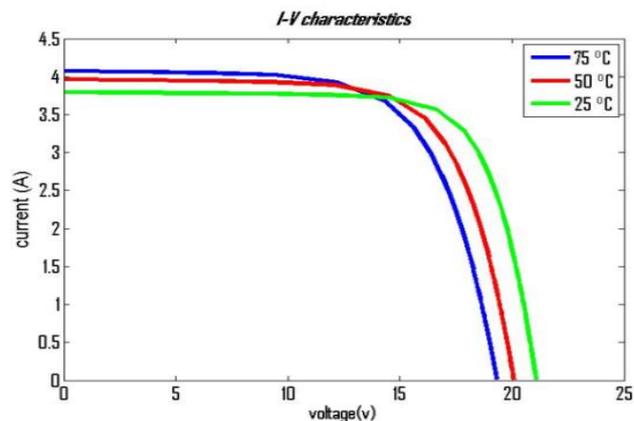
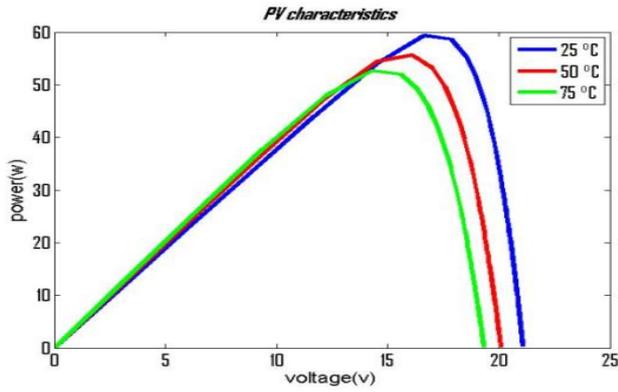**Fig.12** I-V Characteristics at different temperature with constant irradiance

Fig.13 P-V Characteristics at different temperature with constant irradiance

The *I-V* and *P-V* characteristics under varying temperature and constant irradiance are depicted in Fig.12 and Fig.13 respectively. A decrease in voltage is observed by increase in temperature as seen from Fig.12 and decrease in PV power output is observed with increase in temperature, as seen from Fig. 13.

PV characteristics by varying number of arrays in series and parallel is plotted in Fig.14. It is observed that with increase in number of arrays in series and parallel, the power and voltage output of the PV array increases.
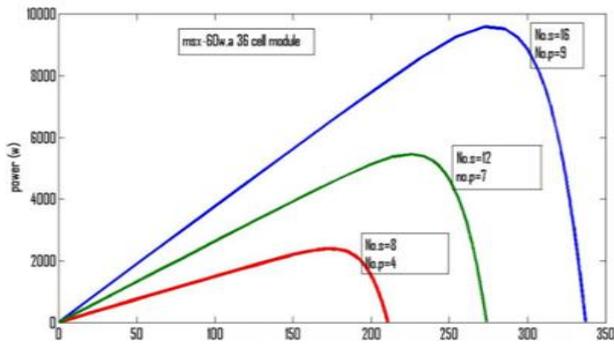

Fig.14 P-V characteristics by varying number of panels connected in series and parallel
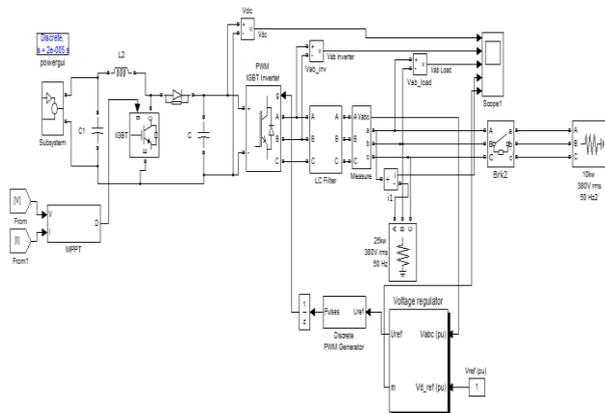
Simulation Results and DISCUSSION

Fig. 15 Simulink model of standalone inverter with load

SAPV in corresponding MPPT is modeled and shown in Fig.15. The simulation is run for 6 s and insolation is varied at an interval of 2 s. Insolation is initially set at $600 w/m^2$ from 0-2 s, after that insolation is set at $800\ w/m^2$ from 2-4s and finally insolation remains at $1000 w/m^2$ for remaining time as shown in fig.16.
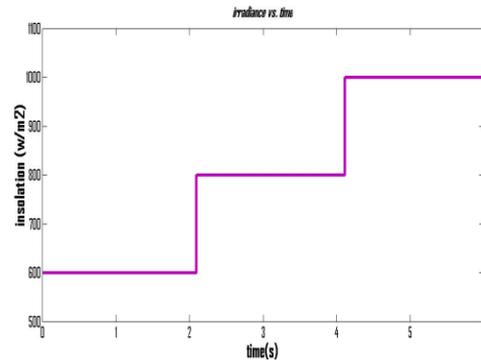

Fig.16 Insolation level (W/m^2 vs. sec)

Table 2 Maximum power points at different irradiations

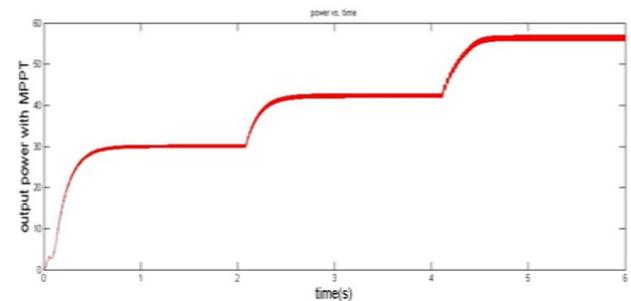| *PV* module			
irradiance(w/m^2)	V_{mpp}	I_{mpp}	P_{max}
1000	16	3.7	59.2
800	15.9	3.1	49.3
600	15.6	2.35	36.66

Fig. 17 MPPT power vs. time

Table 2 represents the maximum power output (P_{MP}), voltage of MPP (V_{MP}) and current of MPP (I_{MP}) under different irradiance level for fixed resistive load. It is observed from maximum PV power output curve as plotted in Fig.17, that as the insolation level increases, the maximum power output of the array also increases and remains in steady state till further change in insolation is observed.
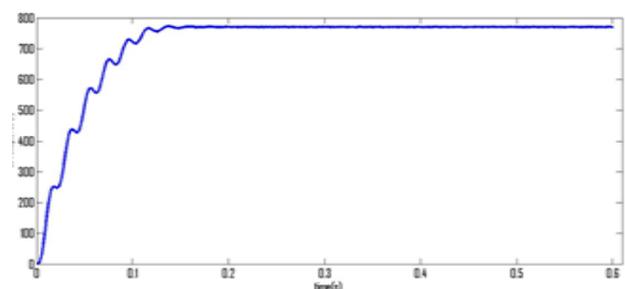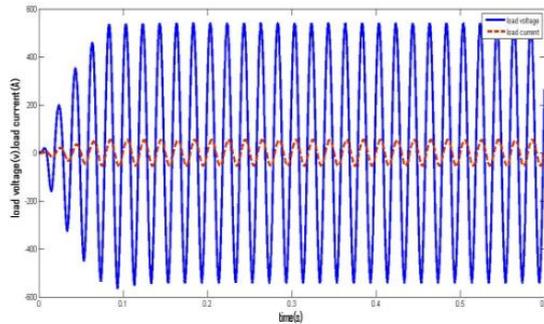

Fig. 18 DC output voltage

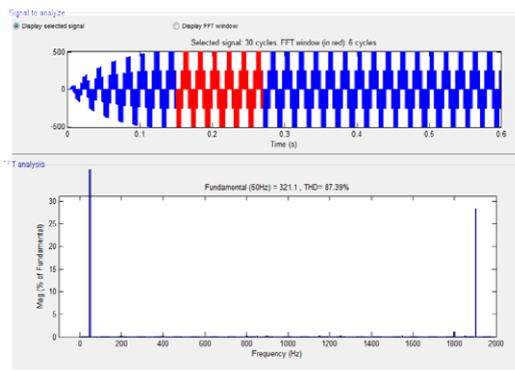**Fig.19** load voltage and current for active load
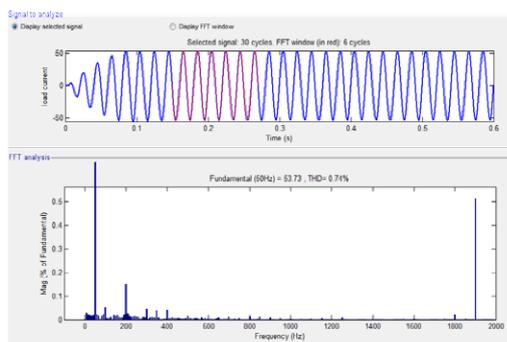

Fig.20 THD of inverter output phase voltage

Fig. 21 THD of line current at load terminals

The SAPV system is feeding a load of 25 KW,381V rating. Voltage profile of DC link capacitor is presented in fig. 18 and the line to line voltage across load and the current drawn by the load is presented in fig.19.It is observed from fig.18 that the DC link voltage is maintained at a constant level of 781V throughout the simulation causing the converter to produce three phase Ac voltage of 381V(rms, L-L)and current of 51 A. As the load is purely resistive, the waveforms of voltage(blue) and current (red) are in phase ,as depicted in fig. 19.

The inverter output voltage has a total harmonic distortion (THD) of 87.39%.,as represented in Fig. 20.To minimize the harmonic distortion, a LC filter is used at the output stage of inverter. As a result, the THD of line current at load terminals is 0.92% , as seen from fig.21.

Conclusion

In this paper, the model of standalone photovoltaic system is implemented. The system contains a simple model of photovoltaic array, MPPT with boost converter and an inverter. The system can supply power to a mainly resistive dc load and an RLC ac load (25kw). The loads are just chosen to match the power generated by the PVA. Actually the voltage at dc load bus and the both voltage and frequency at ac load bus must be controlled and kept constant for the users. The control part is done using voltage regulator. Hence, the PVA modeling and regulator modeling are included in this work. P&O method of MPPT control has been used in this paper. The various values of the voltage and current obtained have been plotted in the IV curves of the PV array at different Insolation levels and simulation results of MPPT and SAPV inverter verify the correctness of the proposed model.

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