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Research paper

Modeling, simulation and experimental investigation of closed loop MPPT based single phase stand alone photo voltaic system using particle swarm optimization technique

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Abstract

Standalone photovoltaic (PV) systems are implemented to perform independently from the utility grid. Such system are beneficial for certain AC as well as DC loads; that too especially where conventional energy cannot reach. To make such system more efficient and independent, a closed loop control could be employed. This research paper presents a novel approach to model and simulate a closed loop maximum peak power tracking (MPPT) based single phase stand alone system using particle swarm optimization (PSO) technique. Based on the simulation results, an experimental investigation has been successfully carried out.

Keywords: *Controller, converter, filter, inverter.*

1. Introduction

Lot of research work is being carried out, in the area of renewable energy sources such as wind, solar, biomass, hydro, tidal, geothermal etc. In the country like India, the potential of solar energy is enormous and also government of India is promoting to install various system based on renewable energy by implementing various schemes. In PV system, PV modules are having a non linear V-I characteristics and also the performance of modules varies with respect to changing of weather conditions [1]. Therefore an appropriate MPPT technique is essential to be implemented. This research paper concentrates on Perturb and Observe method in order to gain maximum power from the module [2]. The developed model also consists of battery backup which is a critical part of any closed loop PV system. Optimization problems are mostly observed in various fields of power system technology. The fact that many times optimization problems, when modeled in correct way, are of non-convex and also discrete in nature. This has encouraged many researchers to develop and implement new optimization techniques to overcome such difficulties. Particle Swarm Optimization (PSO) is one of the recent developed optimization techniques with many important features. Previous experimentations of employing PSO in many applications in power system technology have indicated potential of such technique.

Therefore full bridge inverter with closed loop control using PSO technique is used to generate AC output which has improved the system performance. Based on the simulation results a prototype of 1 kilowatt standalone PV system is developed and practically investigated.

2. Proposed stand alone PV system

The closed loop MPPT based standalone PV system as shown in fig 1 has been modeled to work independently from the grid.

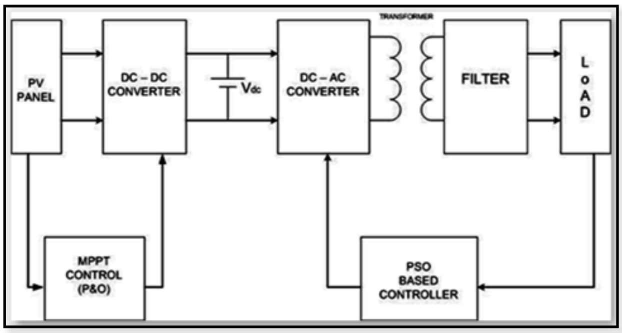

Fig. 1: Block diagram of standalone PV system

From the block diagram it could be observed that the output of MPPT controller is applied to DC-DC converter with adjustable duty ratio in order to improve the performance of DC-DC converter [3]. The inverter block is fed with the feedback controller using PSO technique which senses the voltage and current from the output of inverter and improves the PWM signal fed to the switches of inverter in order to improvise the output AC signal. Also at the output side an AC transformer is considered to boost the voltage to get line voltage. In order to reduce harmonics a LC filter is also considered.

3. Maximum peak power tracking (MPPT) technique

Perturb and Observe (P&O) method is implemented in the MPPT model in which the perturb amplitude is considered to the actual operating conditions [4]. The voltage corresponding to maximum power of the panel is dependent on the solar irradiations and temperature. Considering the V-I characteristics and neglecting the shunt resistance, the voltage of the solar array is given as [5]

$$V = \frac{AkT}{q} \ln\left(\frac{I - I_{ph} - I_{sat}}{I_{sat}}\right) - r_s I \quad (1)$$

Where V is the PV array voltage, I is PV array current, I_{ph} is current generated from photons as a function of temperature and solar irradiations, I_{sat} is the reverse saturated current, q is the electron charge, k is the Boltzmann's constant, A is the ideality factor, T is absolute temperature and r_s is resistance.

The light generated current and the reverse saturated current is expressed as:

$$I_{ph} = [I_{scr} + k_I(T - T_r)]S \quad (2)$$

$$I_{sat} = I_{rr}\left(\frac{T}{T_r}\right)^3 \exp\left[\frac{qE_g}{k}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right] \quad (3)$$

Where T_r is reference temperature, E_g is energy band gap, I_{scr} is short circuit current at reference temperature, k_I current temperature coefficient, S is solar irradiation and I_{rr} is reverse current coefficient.

Thus in order to obtain the voltage at maximum peak power, the power derivative of current function should be zero when power derivative of voltage function is also zero. Thus maximum peak power could be obtained by using equation 4 given below:

$$\frac{AkT}{q}\ln\left(\frac{I - I_{ph} - I_{sat}}{I_{sat}}\right) + I\left(\frac{AkT/q}{I - I_{ph} - I_{sat}} - 2r_s\right) = 0 \quad (4)$$

If the solar irradiations and the temperature are measured and known, the numerical solution of equation 4 gives theoretical values of optimal voltage. The working point is adjusted by considering P&O method. The optimal voltage V_m is used to consider the voltage perturbations as shown in equation 5.

$$\Delta V = F(V_m - V) + \Delta V_{min} \quad (5)$$

F is positive function which is zero with $V_m = V$.

Under this condition a minimum value for perturbation value is set for achieving real maximum peak power. If $\Delta V_{min}=0$ then P&O algorithm is stopped at maximum value without realizing the real one.

Considering the above concept for P&O, the model for MPPT controller has been developed as shown in fig 2.

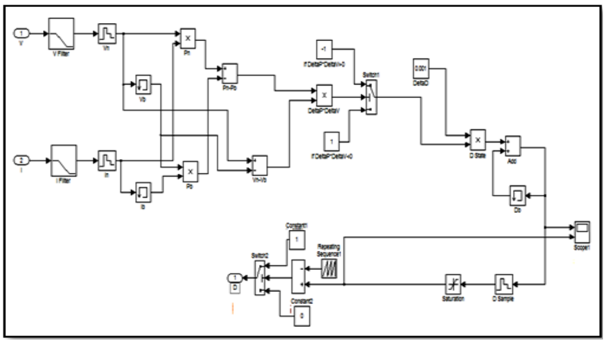

Fig. 2: Model MPPT controller

4. Modeling of PSO based closed loop controller

For design and developing of closed loop controller, output voltage and current are sensed and fed to the feedback loop for improving the switching sequence of power switches. The feedback controller generates an error signal which is applied to the PSO block. The PSO block consists of an optimize device which offers a population based searching in which individuals named particles modify their position (state) with respect to time [6]. Here PSO technique is used to optimize the minimum square error of the load voltage which is obtain by using K_p, K_i and K_d. From the minimized error, the optimum control signals of the inverters have been predicted. By using different types of error load voltage and corresponding control signals, the training dataset has been developed. The model for controller with PSO technique in which the voltage is sensed by the controller to generate an error. This error is optimized by using PSO technique. The modeling of feedback controller with PSO is shown in Fig 3.

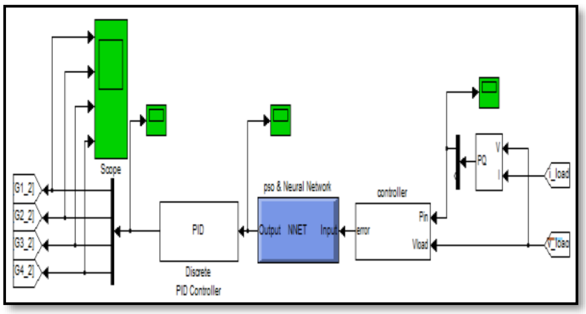

Fig. 3: Modeling of feedback controller

5. Full bridge inverter with transformer isolation and LC filter

Transformer isolated inverters are normally used in PV inverter system. It provides galvanic isolation between DC and AC side for user safety. The transformer also steps up the voltage level suitable for AC loads [7]. The fig 4 shows the inverter topology used in the model.

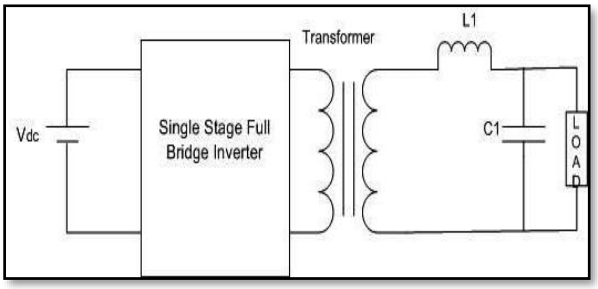

Fig. 4: Full bridge inverter topology

A full bridge inverter topology is most commonly used inverter for high power application. With the same dc input voltage, the maximum output of full bridge inverter is two times that of half bridge inverter. The table 1 shows the switching performance of inverter.

Table 1: Inverter Switching

S_1	S_2	S_3	S_4	V_A	V_B	V_{AB}
ON	OFF	OFF	ON	$V_{dc}/2$	$-V_{dc}/2$	V_{dc}
OFF	ON	ON	OFF	$V_{dc}/2$	$V_{dc}/2$	$-V_{dc}$
ON	OFF	ON	OFF	$V_{dc}/2$	$-V_{dc}/2$	0
OFF	ON	OFF	ON	$-V_{dc}/2$	$V_{dc}/2$	0

At the output of full bridge inverter a LC filter is used to lower the harmonics generated by the pulsating modulated waveform [8]. While designing LC filter, the cut off frequency is chosen such that the lower order harmonics are eliminated. The capacitance value should be maximized and the inductance value should be minimized at the selected cut off frequency of filter.

The values of L and C components are determined to minimize the reactive power. With the selected values of L and C, the voltage waveform of inverter could be sinusoidal with linear load and steady state conditions as output impedance will be zero [9]. But with non-linear load the output waveform may be distorted for

which a closed loop system is employed. Under closed loop system, considering the relation between system time constant and filter capacitor value, the capacitor value is decided.
Figure 6 shows the equivalent circuit of inverter.

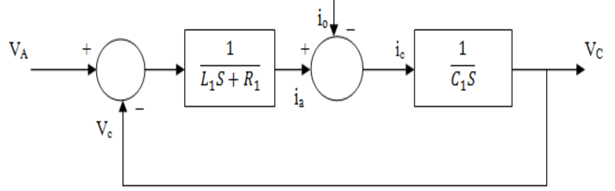

Fig. 5: Equivalent circuit of inverter and filter

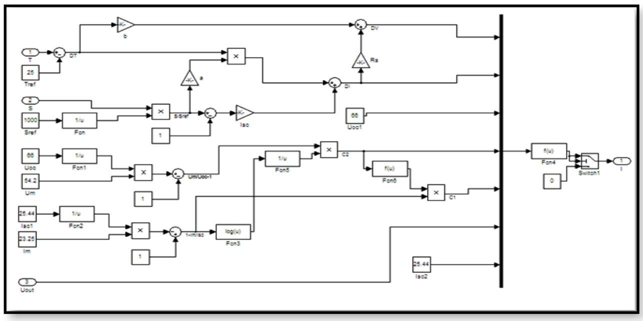

Fig. 6: Modeling of PV module

Considering fig 5, the basic equation for overall transfer function in S domain is given by

$$V_c(S) = \frac{1}{L_1C_1S^2+JR_1C_1}V_A(S) - \frac{L_1S+R_1}{L_1C_1S^2+JR_1C_1S+1}I_o(S) \quad (6)$$

Considering S = jw

$$V_c(jw) = \frac{1}{-w^2L_1C_1+JR_1C_1}V_A(jw) + \frac{jwL_1+R_1}{w^2L_1C_1+wR_1C_1-1}I_o(jw) \quad (7)$$

To determine the transfer function

$$V_{A(S)} - SL_1i_a(S) - R_1i_a(S) - V_c(S) = 0$$

$$\frac{V_A(S)}{V_c(S)} = 1 + (SL_1+R_1)\frac{i_a(S)}{V_c(S)}$$

But $V_c(S) = \frac{I_c}{C_1S}$

$$\frac{V_A(S)}{V_c(S)} = 1 + (SL_1+R_1)SC_1\frac{i_a(S)}{i_c(S)} \quad (8)$$

$$i_c(S) = i_a(S) - i_0(S)$$

$$i_a(S) = i_c(S) + i_0(S)$$

$$i_a(S) = i_c(S) + \frac{V_c(S)}{Z_L}$$

Where Z_L is load impedance and $V_C(S) = i_c(S)/SC_1$

$$\frac{i_a(S)}{i_C(S)} = 1 + \frac{1}{SC_1Z_L} \quad (9)$$

Putting equation 9 in 8

$$\frac{V_A(S)}{V_C(S)} = 1 + (SL_1+R_1)SC_1\left(1+\frac{1}{SC_1Z_L}\right)$$

$$\frac{V_C(S)}{V_A(S)} = \frac{Z_L}{S^2L_1C_1 + S(L_1+R_1C_1+Z_L) + (R_1+Z_L)} \quad (10)$$

Considering equation 10, step response, corner and cross over frequency by using bode plot and stability with root locus could be obtained.
The condition for selecting values of inductor (L) and capacitor (C) for filter equation 11 should be satisfied

$$\frac{X_L}{X_C} = \frac{34.33}{f^2} \quad (11)$$

6. Modeling of closed loop MPPT based PV system with PSO

Based on the theoretical approach explained in the earlier section, a complete model of closed loop MPPT based photovoltaic system with PSO technique has been developed. As shown in figure 6 a PV module block set is developed by considering different parameters such as Insolation (S), Temperature (T_{ref}), open circuit voltage (V_{oc}), short circuit current (I_{sc}), maximum Voltage (V_m) and maximum current (I_m).

The model of PV module with DC to DC converter and MPPT technique has been applied to transformer isolated full bridge inverter with PSO based closed loop system [10],[11]. A LC filter has also been introduced to reduce the harmonics. Figure 7 shows the complete model.

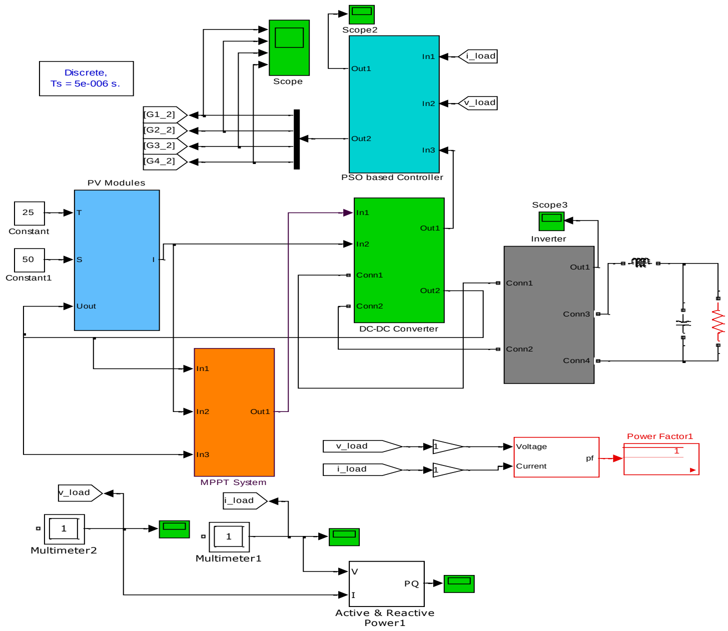

Fig. 7: Closed loop PSO base PV system

7. Hardware Experimentation

Based on modeling and simulation an experimental setup of 1kilowatt PV system has been installed in the lab. For which four PV modules of 250 watt each were installed on the roof top. The installed module successfully charged 24 volt battery. The output of battery was given to a developed full bridge inverter for generating AC output. Figure 8 shows the installed setup of PV system.

Fig. 8: Hardware implementation of PV system

The hardware model was tested with different loads for various parameters such as voltage, current, THD, active and reactive power and power factor [12].

8. Results and discussion

The MATLAB/Simulink model for PV module with MPPT system was initially developed. For MPPT algorithm with Perturb and Observe (P&O) method was considered. The developed model was able to generate maximum voltage and current for maximum power. Voltage was stable at 30 volts and current was stable at 1.2 Amp. The waveform shown in figure 9 shows the voltage and current of MPPT.

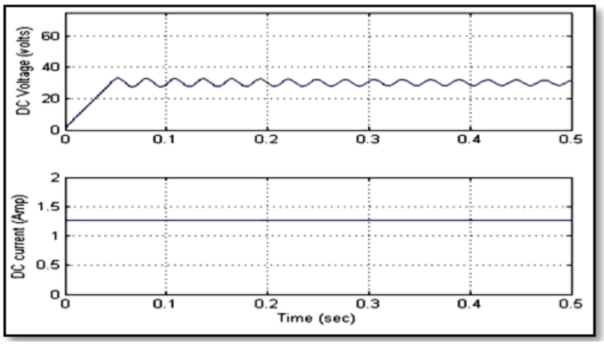

Fig. 9: Voltage and current from MPPT system

The output of MPPT was applied to battery. The battery was successfully charged to around 28 volts as shown in fig 10.

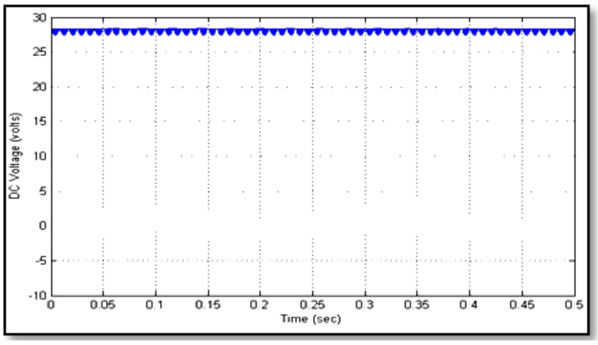

Fig. 10: Battery Output

For improving the switching of inverter switches a PSO based feedback controller was used. The error signal generated from controller was given to the PSO and Neural Network block. The PSO technique as per the training datasets has been used to optimize the minimum square error value of load voltage. Thus figure 11 show the predicted signals of the inverter for improving the PWM signals.

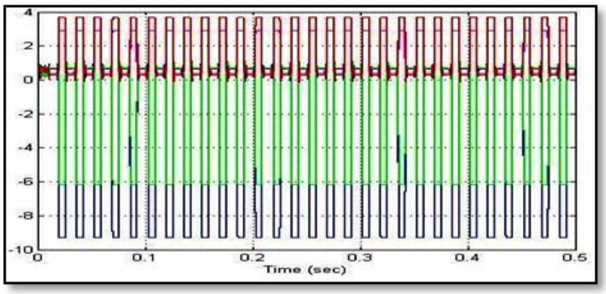

Fig. 11: Output of PSO

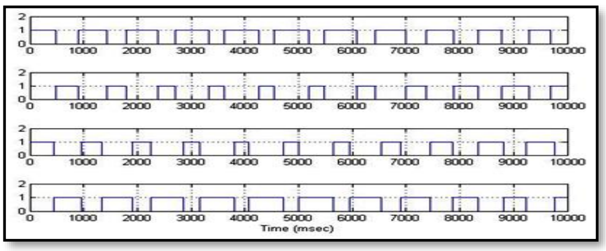

Fig. 12: PWM signals

The improved pwm signals as shown in fig 12 were given to transformer isolated full bridge inverter with LC filter and output AC voltage and current were observed. Fig 13 shows the AC output voltage and current. The voltage and current waveforms were perfect sinusoidal signals. With voltage amplitude equal to 220 volts and current amplitude equal to 1.98 amp.

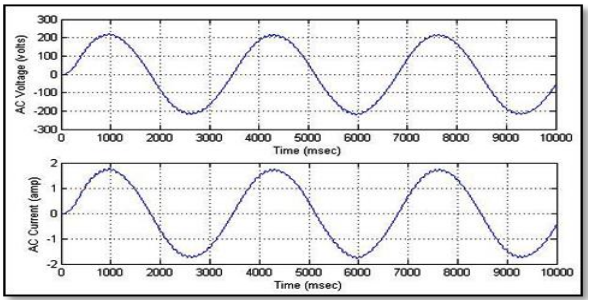

Fig. 13: Output AC voltage and current

The current THD value for the developed PV model without PSO was found to be 26.62 % where as with PSO was found to be 1.78% which is well below the accepted value as per IEEE standards. Fig 14 shows the FFT window which shows the harmonic value as per the selected signal, in the form of bar chart. As per the FFT window shown the THD was obtained for 20 cycles.

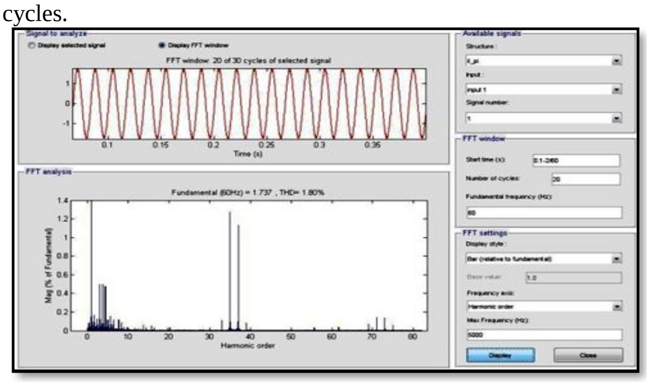

Fig. 14: FFT window

After obtaining the results for simulation model, the hardware prototype for1 kilowatt was experimented and tested. The output voltage and current was observed on DSO as shown in figure 15.

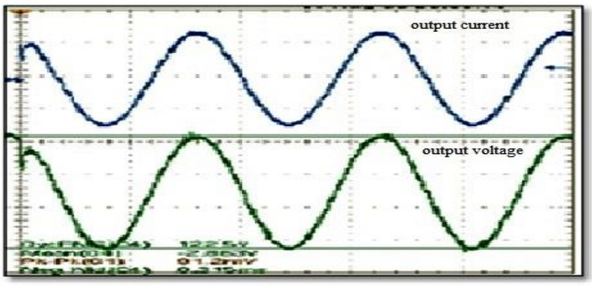

Fig. 15: Output current and voltage of prototype

Further the prototype was tested for number of loads. The readings of voltage, current, crest factor and percentage THD are tabulated in table 2.

Table 2: Values for Voltage, Current, Crest Factor and THD

S.No.	Load (watt)	Output Voltage (volts)	Output Current (amp)	Crest Factor	THD (%))	Error band ratio
1.	545	230	2	1.38	14.8	0.97
2.	618	230	2.2	1.43	13.5	1.01
3.	691	229	2.4	1.47	12.8	1.03
4.	725	228	2.6	1.49	11.9	1.05
5.	758	230	2.7	1.41	11.7	0.99
6.	794	229	2,8	1.36	11.6	0.96
7.	829	228	2.9	1.38	10.8	0.97
8.	900	228	3.1	1.42	10.4	1.00
9.	910	230	3.3	1.45	9.8	1.02

9. Conclusion

By considering PSO technique in MATLAB/Simulink model the pwm signals were improved based on the output voltage and current sensed by the controller. The MPPT technique was able to stabilize the DC signal for charging of battery at nearly 28 volts. The output AC voltage and current of inverter was very close to sinusoidal. Also the current THD value was 1.78% which is well below as per IEEE standard. The hardware prototype model for 1 kilowatt was also experimented and investigated successfully. As per the observation shown in table 2 for the 1 kilowatt prototype model, the crest value at different load values was very near to the ideal value of 1.414 which gives the perfection in sinusoidal output. Based on the different crest value the error band ration based on the ideal value of crest factor has also been tabulated and it is showing satisfactorily results. As per table 2 it is also observed that the THD value was decreasing when the load was increased to the system rated value of 1 kilowatt. At nearly full load of 910 watt the THD was 9.8 %.

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