Design and Control of Small Power Standalone Solar PV Energy System

Neha Adhikari [1] Bhim Singh [2] A.L.Vyas[1]

Abstract– This paper deals with the analysis, design and control of a small power standalone solar photovoltaic (SPV) generating system. A PV array of 33V-43.2V is taken as an input and its output voltage is achieved as 360V dc using a flyback converter. The battery is charged at this voltage and using a single-phase voltage source inverter (VSI) it is converted into a single phase ac of 220Vac, 50 Hz. A closed loop control for maximum power point tracking (MPPT) and a PI (Proportional Integral) controller for output voltage control of VSI are used to optimize the system. Perturbation and observation method is applied for MPPT. The simulation of the developed model of the designed SPV system is performed in Matlab platform. Simulation results are presented with linear and nonlinear loads to demonstrate its satisfactory performance.

Keywords–Battery, Isolated flyback converter, Maximum power point tracking, Solar photovoltaic generation, Standalone system, Voltage source inverter.

I. INTRODUCTION

Solar photovoltaic (SPV) systems convert sunlight directly into electricity. A small power system enables home-owners to generate some or all of their daily electrical energy demand on their own roof top, exchanging daytime excess power for its energy needs in nights using SPV generation, if it is supported by the battery back-up. A SPV power system can be used to generate electric energy as a way of distributed generation (DG) for rural areas [1]. Several approaches have been proposed to improve efficiency of SPV system and to provide the proper ac voltage required by residential customers. For this purpose, dc-dc converters have been explored extensively to meet the required electric energy demands by these systems using a battery back-up [2]. A single switch flyback converter is designed with transformer isolation to charge the battery. The battery voltage is converted into ac supply using a voltage source inverter (VSI) and a filter. The design of a solar power system is a process which involves many variables that have to be adjusted in order to obtain optimized parameters for system components.

This paper demonstrates a step-by-step procedure to design different blocks that constitute the PV array, a controller for maximum power point tracking, a dc-dc flyback converter, a battery block, a VSI, a filter and the feedback control loop with PI (Proportional-Integral) controller. Detailed performance analysis is carried out for analyzing the controller performance in varying loading conditions [3].

The paper first received 13 Dec. 2010 and in revised form 29 Aug 2012.
Digital Ref: A190711313

[1] Instrument Design Development Centre, IIT Delhi, Hauz Khas, New Delhi-110016, India E-mail: nehaadhikari2008@gmail.com, alvyas@iddc.iitd.ac.in
[2] Dept. of Electrical Engg., IIT Delhi, Hauz Khas, New Delhi-110016, India, bhimsinghiitd@gmail.com

The analysis of the standalone system and results are obtained by simulations to supply average load of 300W power rating under variable input voltage range by a PV array.

II. PROPOSED SYSTEM CONFIGURATION

Fig.1 shows a block diagram of the solar PV energy conversion system with a dc-dc converter, a battery, a VSI, an output filter and the feedback control loop.

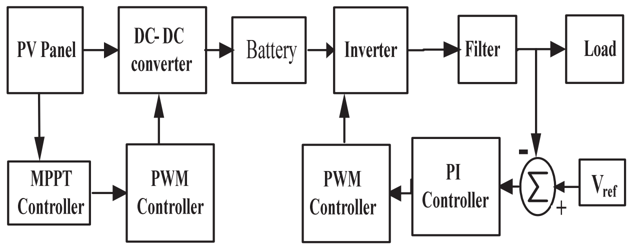


Fig.1: Block diagram of system configuration

Here, a flyback converter is operating in discontinuous conduction mode (DCM) with a very simple feedback control, which needs only output voltage sensing. The flyback converter in DCM operation is much frequently used than continuous conduction mode (CCM) operation, because the DCM contains an inherently smaller transformer magnetizing inductance, that responds more quickly and with a lower transient output voltage spike to rapid changes in output load current or input voltage. Here a flyback converter is used at the input voltage side with a feedback control loop that contains MPPT algorithm and generates PWM signal for the flyback converter and output of this converter is used to charge the battery. The perturbation and observation method is used for MPPT of PV panel. A feedback controller is applied to VSI under varying loads for regulating output voltage. The output voltage of VSI is compared with the reference output voltage and the error voltage signal is processed in the output voltage controller *G(s)*, which generates the PWM signal output for switching device of the VSI. Thus it a low cost solution for controlling duty cycle of switches and gives constant output voltage at varying loads [4-5]. Fig.2 shows the detailed circuit of proposed system.

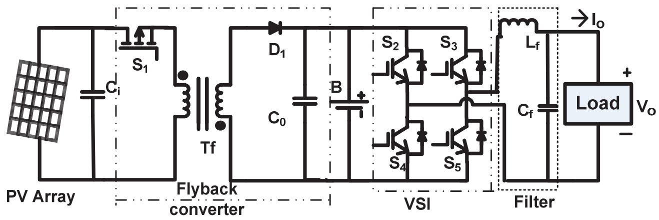


Fig.2: Proposed configuration of solar PV energy system with a flyback converter and a single-phase voltage source inverter

For modeling the PV array, the variation in solar radiation and temperature is also considered for analyzing its performance in different operating conditions.

III. Operating Principle of System Components

Solar-PV array characteristics are varying with environmental conditions and to capture the maximum energy, an MPPT controller is used with a flyback converter.

A. Flyback Converter

A flyback converter is a simplest topology of isolated dc-dc converter because it has only one switch, one transformer and there is no inductor at output stage. The topology of a flyback converter used for this system is shown in Fig.3.

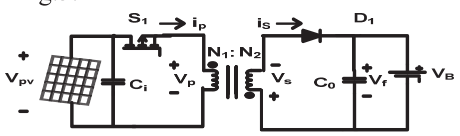
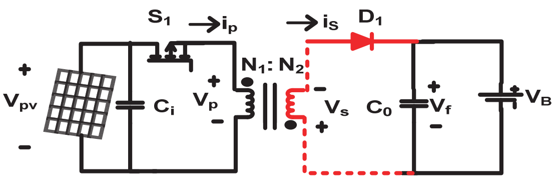
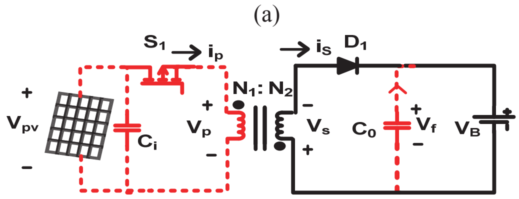


Fig.3: Circuit of flyback converter

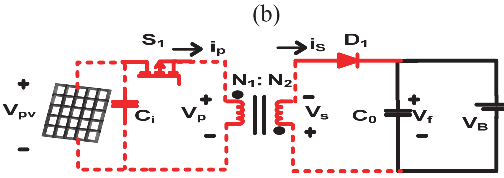
A transformer is used here to eliminate any direct electrical connection between the PV array and the output of the converter power stage. It also has an advantage in terms of cost because of less number of components. Absence of an inductor at output side not only simplifies the circuit but also makes transient response faster. Here a transformer is in inverting mode as polarity of both primary and secondary windings are not same. Basic operation of this converter can be stated as energy is stored in primary winding when the switch is turned on and transferred to secondary winding when the switch is turned off [6]. When switch S_1 is on, a voltage is applied on the primary winding and it causes primary winding current to rise. In this period, the secondary winding and diode are oppositely polarised, a load current is supplied by a capacitor. When switch S_1 is off, stored energy in the primary winding is transferred to secondary winding and load is fed by this secondary winding current. Equivalent circuits for the flyback converter operating in discontinuous mode are shown in Fig. 4 and different operating cases are shown in Table-1



(a)



(b)



(c)

Fig. 4: Different operating conditions of flyback converter (a) Case-1 (b) Case-2 (c) Case-3

Table 1 shows the different operating conditions of the flyback converter during one switching cycle. At initial stage, the current through the primary winding is zero.

Table1: Different operating conditions

	Case-1	Case-2	Case-3
Switch	On	Off	Off
Diode	Off	On	Off

Now in Case-1, the switch S_1 is turned on, diode D_1 is turn off, a voltage across the primary winding is V_p, a current through this increases linearly from zero. In Case-2, switch S_1 becomes turned off, diode D_1 turns on, a voltage across the primary winding becomes $-V_f$. Therefore, the current through the primary winding decreases linearly [6]. This current is reflected to the secondary winding of the transformer and flows through the diode. Once the diode current reaches zero, the diode begins to turn off and the current through the primary winding is zero until the switch is turned on. Thus one switching cycle is complete and as the switch is turned on the next cycle starts as same.

B. MPPT Algorithm

In proposed solar PV energy conversion system, the perturbation and observation method is applied in order to track maximum power point. It is an iterative method of obtaining maximum power point on operating curve of PV array. This algorithm operates by periodically measuring array terminal voltage and current and increments or decrements them after comparing it to the change in output power. Here operating voltage of PV array is perturbed by a finite increment value and due to this, the change in output power is observed. If this change is positive then it shows that operating point is moving closer to the maximum power point (MPP) else it moving away. This determines the direction of next perturbation [7]. The maximum power point can be determined when dP/dV =0, where P is the output power and V is the output voltage of PV array. As the power-voltage relationship of a typical PV module is not linear, the maximum power point can be tracked using this algorithm when condition dP/dV =0 is true for any value of solar radiation and temperature.

C. Voltage Source Inverter and Filter

A full-bridge voltage source inverter (VSI) is used here which consists of four switches. The function of the VSI is to convert 360 V_{dc} voltage supplied by the dc-dc converter into an ac of 220Vrms 50 Hz. Two complimentary PWM pulses are generated by the sinusoidal PWM controller. The basic principle in generating pulses with sinusoidal PWM is to divide the period of the desired sine wave output into number of intervals. In each interval, the control signal remains on for part of the time and off for the other part of the time. The ratio of the “on time” to “off time” at any given instant determines the amplitude of the desired output signal commonly known as duty cycle[8], which is fed to IGBTs (Insulated Gate Bipolar Transistors) of the VSI. One signal is sent in pair to IGBTs S_2 and S_5. The other signal is sent in IGBTs S_3 and S_4.This signal is fed like this as IGBTs $S_2$and S_5 remain on for some period and S_3, S_4 remain OFF for that time and vice-versa. Switches are one of the key components of the VSI. Its output pulse amplitude and waveform have relationship with the power switch of the switching characteristics. It affects the system efficiency and regulation characteristics. Fig.5 shows the topology of VSI and controller schematic.

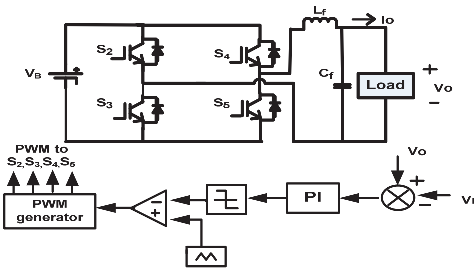


Fig.5: Topology of VSI and PI controller

The output signal from this full-bridge VSI is a pulse waveform which contains the desired output waveform along with frequency components at or around harmonics of the switching frequency. A low-pass filter is here utilized to extract the desired output voltage (50 Hz fundamental frequency) by separating it from the switching frequency.

D. PI Voltage Controller

To get good quality output voltage from a VSI a reasonably smooth dc voltage is required at input side, however this can not be guaranteed always so a PWM control technique at VSI side is used to overcome this problem. Fig. 5 shows the block diagram of the PI controller. An instantaneous voltage error is fed to a proportional integral controller. The integral component in this controller improves the tracking by reducing the instantaneous error between the reference and the actual voltages. The resulting signal is compared with a triangular carrier signal and the error is forced to remain within the band defined by the amplitude of the triangular waveform [9]. Thus it generates switching pulses for VSI.

IV. Design of System Components

The proposed system with a flyback converter, a battery, and a voltage source inverter is designed step by step procedure as follows.

A. PV Array Selection

Here a system is designed to feed an average load of 300W so the PV array is taken of total 750W and additional energy to charge the battery. Here three panels of 250W rated power are selected and connected in parallel to achieve the full power of 750W.

B. Design of Flyback Converter

In the flyback converter, during on time of the switch, the energy is stored in the flyback transformer while the load current is supplied by the output capacitor and during off time of the switch, the stored energy in the flyback transformer is delivered as the load current and to the capacitor for charging. In the flyback converter, the duty cycle is restricted up to 50%. This is due to time required to empty the flyback inductor flux to the output capacitor. The different components of the flyback converter are designed using basic equations. Table-2 shows the design equations for the proposed flyback converter [10-12]. Here this flyback converter is designed with a 100 kHz switching frequency in DCM operation. A battery is used at high voltage side of 360 V. The solar PV panel supplies at 85-120V with a little variation in the voltage to the converter, where it converts it to 360 V dc and the battery is charged at this voltage, which is supplied to the VSI for generating 220Vac at 50 Hz. Using equations given in Table 2, the parameters are calculated for the flyback converter at rated power of 750W.

Table 2: Design Equations and Calculated Values for Flyback Converter

Name of Component	Equation for Flyback	Calculated Value
Turns Ratio	$n=\dfrac{N_2}{N_1}=\dfrac{\eta D_{\max}V_{in}}{(1-D_{\max})V_o}$	1:4
Magnetizing Inductance	$L_{m(\max)}=\dfrac{V_{in}D_{\max}}{f_{sc}\Delta i_{Lm}}$	1.2 mH
Output Capacitance	$C_o=\dfrac{D_{\max}V_o}{f_{sc}R_L V_{cpp}}$	20 µF
Switching Frequency	f_{sc}	100 kHz

Considering, f_{sc} (Switching Frequency of converter switches)=100kHz, L_m (magnetizing Inductance)=1.2µH, V_o(output voltage)=360V, V_{in}(Input voltage)= 85-120 V, C_o (output capacitance, $n=N_2/N_1$ (Turns ratio for flyback transformer), P_{omax} (maximum output power)=750W, D_{max}(maximum duty cycle for operation in DCM)=0.5, η=90%, V_{cpp} (allowed ripple voltage across the output capacitor) =1V.

C. Design of Battery System

The battery plays an important role in case of the solar power system. The battery stores part of the energy generated by the solar PV power source and delivers to the load during the periods when the solar power source is unable to supply the power to the load due to any reason. The capacity of the battery depends on the daily load and days of autonomy [13]. To calculate the battery capacity for feeding 250W power at 360V, (1) is used as.

$$\text{Total Daily Load(AH)}=\frac{\text{No. of Amps}\times\text{No. of Hrs}}{\text{Day of Operation}} \quad (1)$$

The battery is considered to deliver a power for 16 hours. So here it is taken as 30 batteries of 12V, 11Ah in series connection.

D. Design of Voltage Source Inverter

A topology for a VSI chosen here is a full bridge VSI. After selecting the VSI topology, the next step is to select its device rating. To find rating of VSI switches a rated load condition as well as worst operating conditions of the load is considered. An average load of the system is considered as 300W. So the VSI should be designed to withstand at this load which gives the rated VSI output power 375VA and at a power factor of 0.8, at rated phase voltage = 220 V r.m.s. gives a peak current 2.1A. So considering worst case as a nonlinear load e.g. computer loads (SMPS) the device rating of the switches in VSI are taken as 600V, 10A. A closed loop control is also applied for changing the duty cycle of the VSI switches for maintaining the output voltage of the system under varying load conditions using reference sine wave voltage and a PI voltage controller [14].

E. Design of PI Controller

A PI controller can be used for balancing the load variation. It performs satisfactorily during transient under limited operating range and the steady state performance is also excellent. Proportional and integral gains are constants and they are fine tuned for specific operating condition. Here Ziegler-Nichols method is used for tuning of PI controller. Ziegler and Nichols have suggested that the value of K_p (proportional gain) and K_i (integral gain) can be found by setting the controller in the proportional mode and increasing the gain until an oscillation takes place [15]. The point is then obtained from measurement of the gain and the oscillation frequency. According to this method the proportional gain K_p is increased until continuous oscillation is achieved. The period of oscillation (P_c) is measured when the amplitude of oscillation is quite small and the crossover frequency (ω_c), the critical gain (G_c) is obtained from the Nyquist and root locus plot. Characteristic equation of PI controller can be shown as (2). After obtaining all these values, Ziegler and Nichols have suggested [15], that one can set the values of the parameters K_p, K_i according to (3) and (4) as,

$$G_{PI}(S) = \frac{K_p K_i S + K_p}{K_i S} \tag{2}$$

$$K_p = 0.5 G_c \tag{3}$$

$$K_i = 0.5 P_c \tag{4}$$

The G_c is critical gain of the system. P_c is period of oscillation. G_{PI} is gain of PI controller. It is observed that for optimum performance of the controller to guarantee intersections between the triangular and the error signal, it is necessary to set the proportional gain K_p, to unity and the integral gain K_i, equal to the frequency of the triangular waveform. Here they are determined and set accordingly, K_p is set to 1 and K_i is 0.0005.

F. Design of Low Pass Filter

A low-pass (LC) filter is used to get the desired output voltage (50 Hz fundamental frequency) by separating it from the switching frequency and rejects any frequency above its cutoff frequency. The cut off frequency can be obtained by equation (5) as.

$$f_c = \frac{1}{2\pi\sqrt{LC}} \tag{5}$$

The switching harmonics resulted from 20 kHz switching frequency are around half the switching frequency. The switching frequency is selected at 20 kHz to provide clean 50Hz fundamental frequency [16]. The design of an LC filter for VSI is carried out with following equations. Now, the peak inductor current, which is the maximum current that can pass through the inductor can be calculated using (6) as [17],

$$I_L = \frac{2V_m}{R_{L\min}} \tag{6}$$

$R_{L\min}$ is the minimum value of load resistance, and V_m is the peak magnitude of the output voltage. The value of filter capacitor for specific switching frequency may be calculated with the (7) as [17],

$$C = \frac{V_m}{2R_{L\min} f_{si} \Delta v} \tag{7}$$

Δv is the voltage ripple of the output voltage. From the volt–second balance of the inductor, the ratio of "on time" (T_{on}) and "off time" (T_{off}) which determines the duty cycle for VSI is calculated using (8) as [17],

$$\frac{T_{on}}{T_{off}} = \frac{V_d + V_o}{V_d - V_o} \tag{8}$$

where ,V_d is dc link voltage and V_o is output voltage of VSI.

Using the value of minimum switching frequency, the ration of on time and off time can be set as shown in (9) as [17-19],

$$\frac{T_{on}}{T_{off}} = \frac{1}{f_{si}} \tag{9}$$

The value of the inductor is calculated by using (8), (9) and (10).

$$L = \frac{V_d - V_o}{I_L} T_{on} \tag{10}$$

The configuration of LC low pass filter used in this system shown in Fig. 2 and calculated value of L_f=3.8mH and C_f=7.2μF considering V_d= 360V, V_o= 220V, f_{si}= 20kHz, ΔV= 1V, R_{Lmin}= 150Ω for a load of 300W.

V. Modeling and Simulation of System

Different components of solar-PV energy conversion system are modeled in Matlab platform. For maximum power point tracking, a perturbation and observation algorithm is used.

A. Modeling of PV Cell

The complete behavior of PV cells can be described by five model parameters (I_{pv}, N, I_o, R_a, R_b) which represent the physical behavior of PV cell/module. These five parameters of PV cell/module are functions of two environmental conditions of solar irradiance and temperature. Fig.6 shows an equivalent circuit model of PV array.

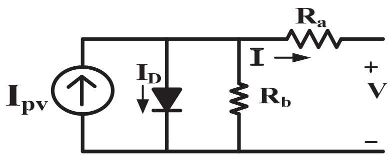


Fig.6: Equivalent circuit of PV array

The PV cell is a nonlinear device and can be represented as a current source, parallel diode, however a practical PV cell model includes the connection of series and parallel internal resistance [20], namely R_a and R_b, which is expressed as equation (11) as.

$$I = I_{pvt} - I_d \left\{ \exp\left(\frac{V + R_a}{V_t N} \right) - 1 \right\} \tag{11}$$

In (11), I = output current of PV, V =output voltage of PV, V_t = $N_s KT/q$ = thermal voltage of array, Ns=number of cells connected in series, q = electron charge (1.60 e^{-19} C), k = the Boltzmann constant (1.380 e^{-23}J K^{-1}), T = temperature of the p-n junction (K), K and N =the diode ideality constant. Here I_{pvt} is current produced by a PV cell, it is function of solar irradiance and temperature. The diode saturation current, I_d is function of temperature, which is expressed in (12) and (13).

The performance of the transformer describing the voltage and current of primary/secondary winding of the transformer under linear load condition is shown in Fig.16. The solar radiation is considered constant at 1000 W/m^2. Due to battery connected in the system with the dc-dc converter it is not affected under varying load conditions of the system.

$$I_{pvt} = (I_{pvt} + K_a \Delta T)\frac{G_1}{G_2} \tag{12}$$

$$I_d = \frac{I_{sc} + K_a \Delta T}{\exp\left[\frac{V_{oc} + K_b \Delta T}{N V_t}\right] - 1} \tag{13}$$

The I_{pvt} is the light generated current at the nominal condition which are 25°C and 1000 W /m^2, $\Delta T = T_1 - T_2$, T_1 and T_2 = actual and nominal temperature in Kelvin, G_1 (W/ m^2) =value of solar irradiation by the PV surface and G_2 =the nominal value of solar irradiation, K_a = short-circuit current/temperature coefficient, K_b = open-circuit voltage/temperature coefficient, I_{SC} = short-circuit current, V_{OC} = open-circuit voltage under the nominal condition. The value for series resistance R_a is taken as 0.1Ω and R_b is 500Ω.

Using these equations, PV array is modeled in Matlab, from the data sheet of SPSM250 solar panel, characteristics of solar panel is taken for modeling the system [20-21]. Results for different conditions of temperature and solar irradiance are obtained through simulation. Table-3 shows the parameters taken from datasheet.

Table 3: Parameters of PV Array

Peak Power	250 W
Open Circuit Voltage	43.21 V
Short Circuit Current	7.63 A
Voltage At Max. Power	35.5 V
Current At Max. Power	7.04 A
No. of Cells	72

Characteristics of PV array are modeled under varying conditions of temperature which is 0ºC to 50ºC and solar irradiance is changing from 200 W/m^2 to 1000 W/m^2. The results obtained for these conditions and performance characteristics of this model are shown in Figs. 7-8.

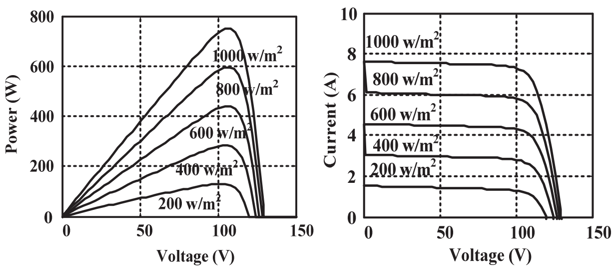


Fig.7: P-V and I-V characteristics of PV array with different solar radiation

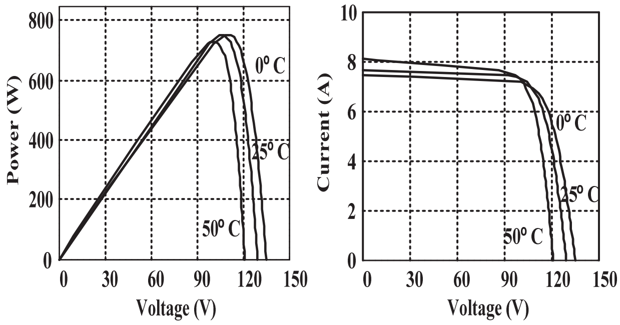


Fig.8: P-V and I-V characteristics of PV array with different temperature conditions

B. Modeling of Battery

For modeling of the battery here, its Thevenin's equivalent circuit model is used. Fig.9 shows the Thevenin's equivalent model of the battery, where R_{eq} is the equivalent series resistance of parallel/series combination of a battery which is usually a small value. For this analysis R_{eq}=0.01Ω. The parallel circuit of R and C describe the stored energy and voltage during charging or discharging [22]. R in parallel with C, represents discharging of the battery, the self discharging current of a battery is small, so the resistance R is large and the typical value of R for this battery is used 10kΩ.

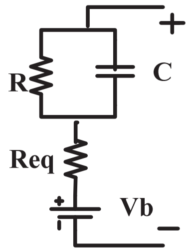


Fig.9: Equivalent model of battery

Here the battery is considered of having 450 W for 16 hours peaking capacity, and variation in the voltage of order of 355 V-365 V. The battery stores the energy from PV system. Its energy is represented in kWh. A capacitor is used in an equivalent circuit for modeling of battery, and the value of capacitance is calculated using (14) as.

$$C = \frac{kWh \times 3600 \times 16}{0.5(V_{max}^2 - V_{min}^2)} \tag{14}$$

V_{max} is the maximum voltage of the battery fully charged and V_{min} is the minimum voltage of the battery when it is fully discharged [22].

The calculated value of C for this battery from equation (14) is C=7200F. The main function of controller is to regulate the current for the battery charging due to variation in the voltage supplied by the PV array. A control circuit can also be added, which protects the overcharging, deep discharge and reverse current flow during discharge [23].

B. Modeling of MPPT Algorithm

For modelling of MPPT its basic principle is considered and Fig.10 shows the operating flowchart of P&O algorithm, V_{pv} and I_{pv} are output voltage and current of PV array and k is the value of variation in voltage to compute next perturbation.

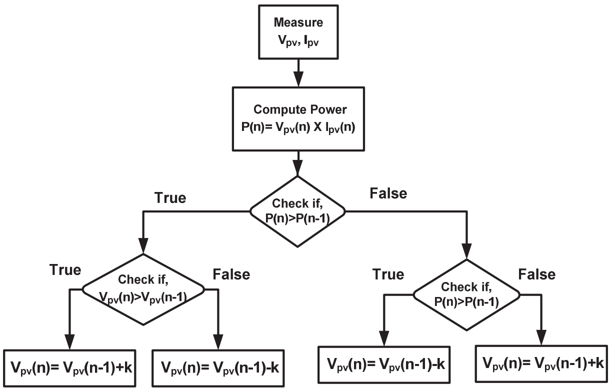


Fig. 10: Flowchart of MPPT

For a given perturbation on the voltage of the panel leads to an increase (decrease) the output power of the PV, then the subsequent perturbation is generated in the same (opposite) direction. As a consequence of the P&O algorithm, when the MPP is reached, the system may oscillate around it and this problem is overcome by reducing the perturbation step size. Here for modeling of this algorithm is carried out in Matlab, the three-point weight comparison method is used, where the perturbation direction is decided by comparing the PV output power on three points of the characteristics curve.

B. Matlab Model of Proposed System

The modeling of the complete system (detailed data are given in Appendices) is carried out in Matlab/Simulink. A PV array is modeled with consideration of changing conditions of temperature and solar insolation, which is modelled as a subsystem having input as temperature and solar insolation and panel are connected through flyback converter.

VI. Result and Discussion

A simulation model is developed of solar PV based power system with a flyback converter in discontinuous mode of operation with maximum power tracking controller for extracting maximum power from PV array and a PI controller in feedback of VSI for load variation in output. Results are obtained for different load conditions. Fig. 11 shows a harmonic analysis of the output voltage and current at linear loads which gives Total Harmonic Distortion (THD) of 2.45% and 2.21% for voltage and current respectively.

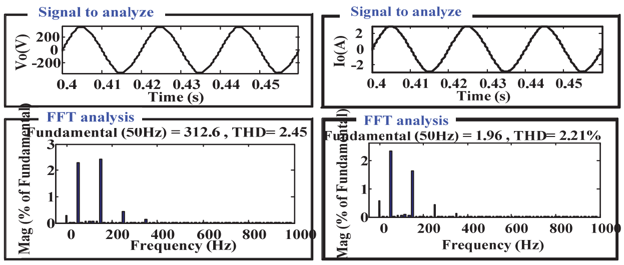


Fig.11: Waveforms and Harmonic analysis of output voltage and current at linear load

Fig.12 shows the performance of the system at a linear load under varying solar radiations. In this figure it is observed that along with the solar radiations, the output voltage of the solar-PV array is varying, while the output voltage of the flyback converter remains same. Thus it validates the performance of the MPPT controller.

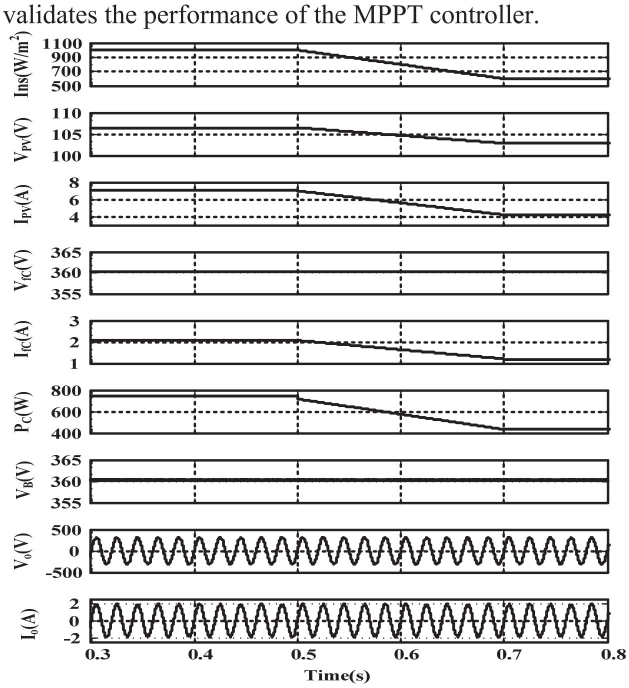


Fig.12 Performance of the system with linear load

In these figures, V_{pv} is output voltage of PV array, I_{pv} is output current of PV array, V_p and V_s are voltages of primary, secondary windings of transformer. I_p and I_s are currents of primary, secondary windings of transformer. V_{fC} is output voltage of the flyback converter. P_C is power. I_{fC} output current of the flyback converter. V_o and I_o are output voltage and current of VSI. For analyzing the performance of this system under nonlinear load condition, an SMPS (Switched Mode Power Supply) is used as a nonlinear load because it has highly nonlinear characteristics and widely used in many applications. Fig.13 shows the results of the output voltage and current of VSI at nonlinear load, which has a crest factor of 2.7 of output load current.

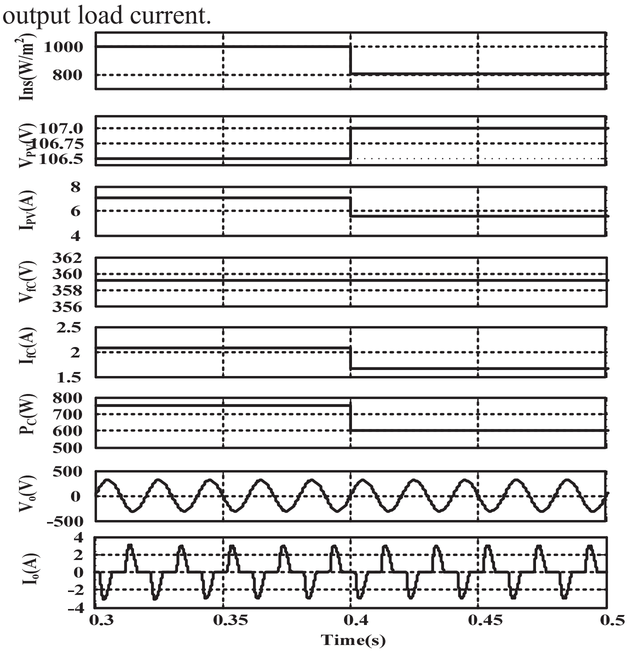


Fig.13: Performance of the system at nonlinear load

Fig.14 shows the harmonic analysis of voltage and current at nonlinear load condition. The voltage THD is as 3.13% only and even when the current THD is as 68.34%.

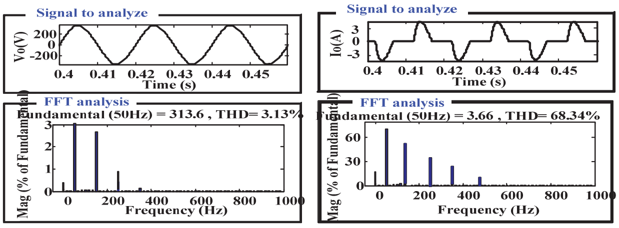


Fig.14: Waveforms and Harmonic analysis of output voltage and current at non-linear load

The system is designed for standalone operation thus the variation in the consumer load is analyzed and the results are presented in Fig.15.

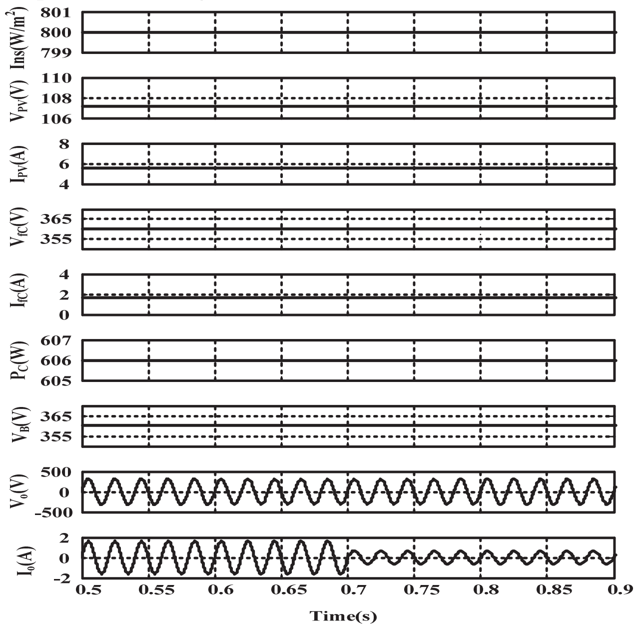


Fig.15: Performance of the system at load variation

The load is varying at time 0.7s and the solar radiation considered remains same at 800 W/m^2, thus the output current changes at the 0.7s and the output voltage is observed as not affected by the load variation. These results validate the performance of the output controller which maintains the output voltage constant in case of load variation load.

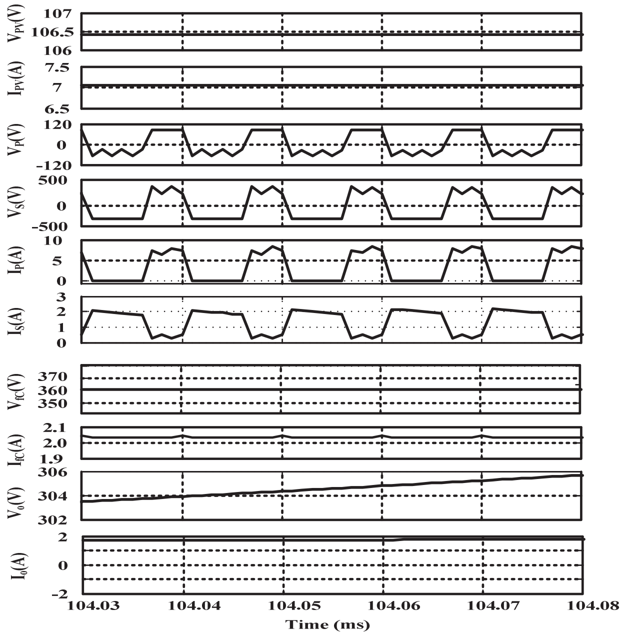


Fig.16: Performance of the system with transformer characteristics

The performance of the transformer describing the voltage and current of primary/secondary winding of the transformer under linear load condition is shown in Fig.16. The solar radiation is considered constant at 1000 W/m^2. Due to battery connected in the system with the dc-dc converter it is not affected under varying load conditions of the system.

The performance of the battery during charging and discharging is shown in Fig.17. It shows that the battery takes charging time with maximum power tracking of 8 hours and capable of supplying full load up to 16 hours, where V_b is the voltage of battery, I_b is current of battery and SOC is charging condition and time is in hours.

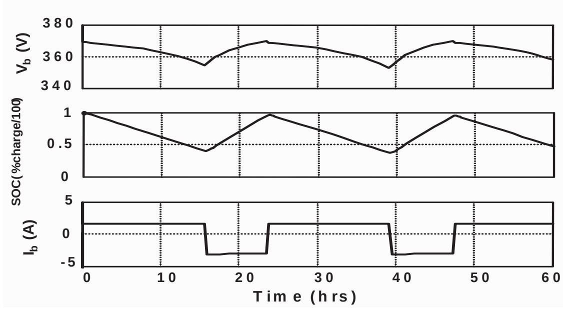


Fig.17: Performance characteristics of battery

VII. Conclusion

The design and performance study of a standalone solar PV energy system have been carried out using a flyback converter, battery and a single phase voltage source inverter. The battery charging has been achieved through maximum power point tracking which gives sufficient backup for 16 hours. The controller performance under various load conditions has been investigated and it has given required response under nonlinear load conditions. The results obtained for harmonic distortion of this system for both linear and nonlinear loads are within the 5% range specified by IEEE-519 standard. Performance of the system for the load variation is improved due to feedback PI control applied to VSI, so depending on the requirement one can choose it for low power application.

Appendices

A. PV Panel parameters

Power = 750W, Open circuit voltage = 129.63V, Short circuit current= 7.63A, Voltage at maximum power = 106.5V, Current at maximum power = 7.04A.

B. Flyback converter

Turns ratio, N_2/N_1= 1:4, magnetizing Inductance, L_m= 1.2 mH, Output capacitance, C_o = 20 µF, Switching Frequency, f_{sc}= 100 kHz.

C. Output Filter

Filter Inductance, L_f= 3.8µH, Filter Capacitance, C_f = 7.2µF.

D. Non-linear load

Fig. 18 shows a nonlinear load used in this system. SMPS with forward converter in isolated mode is considered as R_{eq} for 300W power application, C_s=5mF.

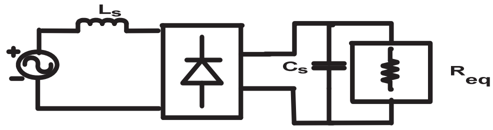


Fig.18: SMPS with forward converter as nonlinear load

REFERENCES

[1] R. Patel, 'Wind and solar power systems', CRC Press, USA, 1999.

[2] Q. Zhao and F. C. Lee, "High-efficiency, high step-up DC-DC converters," *IEEE Trans. on Power Electronics*, vol. 18, no. 1, pp. 65-73, Jan. 2003.

[3] K. Knapp and T. Jester, "Empirical investigation of the energy payback time for Photovoltaic modules," *Solar Energy,* vol. 71, no. 3, pp. 165-172, 2001.

[4] Weidong Xiao, Nathan Ozog and William G. Dunford, "Topology Study of Photovoltaic Interface for Maximum Power Point Tracking," *IEEE Trans. on Industrial Electronics*, vol. 54, no. 3, pp. 1696-1674, June 2007.

[5] N. Mohan, N. Undeland, M. Robbins, 'Power Electronics Converters, Applications and Design,' John Wiley & Sons, USA, 2003.

[6] Nasir Coruh, Satilmis Urgun and Tarik Erfidan, "Design and Implementation of Flyback Converters," in the Proc. of 5th IEEE Conference on Industrial Electronics and Applications, pp.1189-1193, Taichung, 15-17 June *2010.*

[7] J.Salazar, F. Tadeo, C.Prada and L. Palacin, "Simulation and Control of a PV System Connected to a Low Voltage Network," Days of Automatic, Jaén, pp. 1-6, Spain, Sept. 08-10, 2010.

[8] J.A. Gow and C.D. Manning, "Photovoltaic converter system suitable for use in small scale stand-alone or grid connected applications," *IEE Proc-Elecr. Power Appl.*, vol. 147, no.6, pp. 535-543, Nov. 2000.

[9] Yoon-Ho Kim and Hoi-Doo Ha, "Design of Interface Circuits with Electrical Battery Models," *IEEE Trans. on Industrial Electronics*, vol. 44, no. 1, Feb. 1997.

[10] Savita Nema, R.K.Nema and Gayatri Agnihotri, "Matlab / simulink based study of photovoltaic cells / modules / array and their experimental verification," *International Journal of Energy and Environment*, vol. 1, no. 3, pp.487-500, 2000.

[11] F. Blaabjerg, F. Iov, R. Teodorescu and Z. Chen, "Power Electronics in Renewable Energy Systems," in the Proc. of 12th International Power Electronics and Motion Control Conference (EPE-PEMC 2006)*,* pp. 1-17, Aug. 2000.

[12] P. P. Groumpos and G. Papageorgiou, "An Optimal Sizing Method for Stand-alone Photovoltaic Power Systems," *Solar Energy*, vol. 38, no. 5, pp. 341-351, 1987.

[13] Yoon-Ho Kim and Hoi-Doo Ha, "Design of Interface Circuits with Electrical Battery Models," *IEEE Trans. on Industrial Electronics*, vol. 44, no. 1, pp. 81-86, Feb. 1997.

[14] Phoivas D. Ziogas, Eduardo P. Wiechmann and Victor R. Stefanovic, "A Computer-Aided Analysis And Design Approach For Static Voltage Source Inverters," *IEEE Trans. on Industry Applications*, vol. IA-21, no. 5, pp. 1234- 1242, Sept./Oct. 1985.

[15] Tengku Luqman Tengku Mohamed, Mohamed Raimi Hazwani Azman and Zulkifli Mohamed, "Development of Auto Tuning PID Controller using Graphical User Interface (GUI)," in the Proc. of 2nd International Conference on Computer Engineering and Applications, vol.1, pp. 491-495, Bali Island, Indonesia, Mar. 19-21, 2010.

[16] Ayman Saber Elwer, "A Novel Technique for tuning PI-Controllers in Induction Motor Drive Systems for Electric Vehicle Applications," *Journal of Power Electronics*, vol.6, no.4, pp. 322-329, Oct. 2006.

[17] Suvarun Dalapati and Chandan Chakraborty, "A Direct PWM Technique for a Single-Phase Full-Bridge Inverter Through Controlled Capacitor Charging," *IEEE Trans. on Industrial Electronics*, vol. 55, no. 8, pp.2912-2922, Aug. 2008.

[18] Francesco Castelli Dezza, Michele Diforte and Roberto Faranda, "A Solar Converter for Distributed generation able to improve the Power Quality Supply," in the Proc. of 18th International Conference on Electricity Distribution (CIRED), pp. 1-5, Turin, 6-9 June 2005.

[19] E.L. Meyer and E.D. van Dyk, "Assessing the Reliability and Degradation of Photovoltaic Module Performance Parameters," *IEEE Trans. on Reliability,* vol. 53, no. 1, pp. 83-92, Mar. 2004.

[20] Mohd Saifuzam Jamri and Tan Chee Wei, "Modeling and Control of a Photovoltaic Energy System Using the State-Space Averaging Technique," *American Journal of Applied Sciences*, vol. 7, no. 5, pp. 682-691, 2010.

[21] Geoffrey R. Walker and Paul C. Sernia, "Cascaded dc-dc Converter Connection of Photovoltaic Modules," *IEEE Trans. on Power Electronics*, vol. 19, no. 4, pp. 1130-1139, July 2004.

[22] Mohamed H. Beshr and Hany A. Khater, "Modelling of a residential solar stand-alone power system," in the Proc. of 1st International Nuclear and Renewable Energy Conference (INREC10), pp. 1-6, Amman, Jordan, Mar. 21-24, 2010.

[23] G. B. Shrestha and L. Goel, "A study on optimal sizing of stand-alone photovoltaic stations," *IEEE Trans. on Energy Conversion*, vol. 13, no. 4, pp. 373-378, Dec. 1998.

BIOGRAPHIES

Neha Adhikari received her B.E. in Electronics Instrumentation & Control from Rajasthan University, Rajasthan, India, in 2007 and M. Tech in Alternate Hydro Energy Systems from Indian Institute of Technology Roorkee, Roorkee, India, in 2009. Presently she is pursuing research at Instrument Design Development Centre, Indian Institute of Technology Delhi, New Delhi, India. Her field of interest includes Renewable Energy, Instrumentation & Control and Power Electronics.

Bhim Singh was born in Rahamapur, India, in 1956. He received his B.E. from the University of Roorkee, Roorkee, India, in 1977 and his M.Tech and Ph.D. from the Indian Institute of Technology (IIT) Delhi, New Delhi, India, in 1979 and 1983, respectively. In 1983, he joined the Department of Electrical Engineering, University of Roorkee, as a Lecturer, and in 1988 he became a Reader. In December 1990, he joined the Department of Electrical Engineering, IIT Delhi, as an Assistant Professor. He became an Associate Professor in 1994 and a Professor in 1997. His areas of Interests include power electronics, electrical machines and drives, active filters, FACTS, HVDC and power quality. He is a Fellow of the Indian National Academy of Engineering (INAE), the National Science Academy (FNSc), the Institution of Engineers (India) (IE(I)), and the Institution of Electronics and Telecommunication Engineers (IETE). In addition he is a Fellow of the Institute of Electrical and Electronics Engineers (IEEE).

Anoop Lal Vyas obtained Bachelor of Technology in Electrical Engineering in 1972 and PhD in 1989 both from Indian Institute of Technology (IIT) Delhi. Since 1972 he has been working at IIT Delhi in the areas of Signal processing, Electrical and Electronic Systems and has coordinated a number of sponsored projects in these areas. He presently holds a position of Professor and his interests include Electronic Instrumentation, Smart Sensors, Sensor networks and Energy Systems. He is a fellow of Institution of Electronics and Telecommunication Engineers (IETE) and the Acoustical Society of India (ASI). He is also a life member of the Ultrasonic Society of India (USI).