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Development of a simple Power Electronic Controller for Grid Connected PV Systems

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Abstract – This paper presents a simple technique that efficiently tracks the maximum power from the photovoltaic array and delivers it to the grid. A controller has been developed for interfacing PV array with utility grid through a line commutated inverter. A PIC microcontroller together with the multiplier and opamp signal conditioning circuit has been used for the generation of firing pulses to the SCRs in the inverter. Using adaptive step perturb and observe (P&O) algorithm, the firing angle is automatically adjusted to extract maximum power from the solar PV array, which is fed to the utility grid. The complete closed loop scheme has been modelled and simulated in MATLAB environment and the simulation results are compared with experimental results. A PV array consisting of four panels each rated for 80 W, 21.2 V, 5.17 A has been used for the experiment. It is found that the experimental and simulation results have very close agreement.

Keywords: Solar PV array, line commutated inverter, MPPT, grid connected system.

Introduction

Residential photovoltaic (PV) systems have increased over the past decade and hence numerous PV fed grid interactive home inverter systems have been installed [1]. It is anticipated that as PV system costs decrease, residential systems will be installed in increased numbers. Literatures are available concerning the design, protection, safety, economics and operating experience of residential and central-station PV systems.

Many PV systems operate in stand-alone mode [2] - [6]. Such systems consist of a PV generator, energy storage (e.g. a battery system), ac and dc consumers and elements for power conditioning. It has no interaction with the utility grid. The power conditioning system provides an interface between all the elements of the PV systems, giving protection and control. But the problem encountered with the stand-alone PV system is that the terminal voltage falls down the threshold value of the load, if the insolation is very small. In such cases it is forced to have a grid connection of the existing stand-alone PV systems. Although this method is quite feasible, one has to extract the maximum power and deliver it to the grid.

A controlled power interface between solar cells and grid is required to vary the power fed to the grid [7], [8] as per the load conditions. The rural areas of certain countries suffer from scarcity of electrical power. So a control circuit for controlled power transfer is not necessary, instead, a control circuit is needed for maximum power transfer from the solar cells to grid all the time [9], [10].

This paper presents the simulation and development of a grid connected maximum power point tracking (MPPT) system from PV arrays and verified experimentally using a single phase line commutated inverter (LCI). Simulation has been carried out using MATLAB/SIMULINK.

This paper is organized as follows. The complete working of the proposed scheme employing closed loop operation of the LCI for the grid interface and the grid current harmonic elimination using passive filters has been explained in section 2. The analysis of the PV cell used in the simulation is explained in section 3. The methodology of generation of firing pulses for the thyristors in the LCI using PIC16F876 microcontroller is explained in section 4. The proposed scheme has been simulated using MATLAB software, and the simulation results are presented in section 5. An experiment has been conducted on the proposed scheme, and the results are compared with the simulation results in section 6.

The Proposed Scheme

The block diagram of the PV system integrated with the utility grid with a feedback controller is shown in Fig. 1. PV arrays convert the solar insolation into electrical power which is fed to the grid through dc link inductance and LCI. The inductance is used to obtain a steady direct current from the PV panels. Greater the inductance, smoother will be the direct current and vice-versa. The stability of the total scheme will also depend on this inductance. With larger inductance, the thyristors can be allowed to fire at larger firing angles. The critical value of dc link inductance (L_{dc}) to maintain a continuous current is given by [11]

$$L_{crit} = 0.879 \times V_{av} \sin\alpha / I_{dc} \quad (1)$$

where α is the firing angle. The selected value of L_{dc} is greater than L_{crit} to ensure continuous conduction at all times in the chosen PV power range. The LCI transfer the power from the PV panels to the utility grid through an isolation transformer at higher efficiency [12]. The transformer is required to step-up the low voltage equal to the grid voltage. The basic circuit of the LCI is shown in Fig. 2. The average voltage V_{av} at the dc link of the LCI is given by

$$V_{av} = \left(2\sqrt{2}/\pi\right) V_g \cos\alpha \quad (2)$$

where V_g is the phase value of the grid voltage.

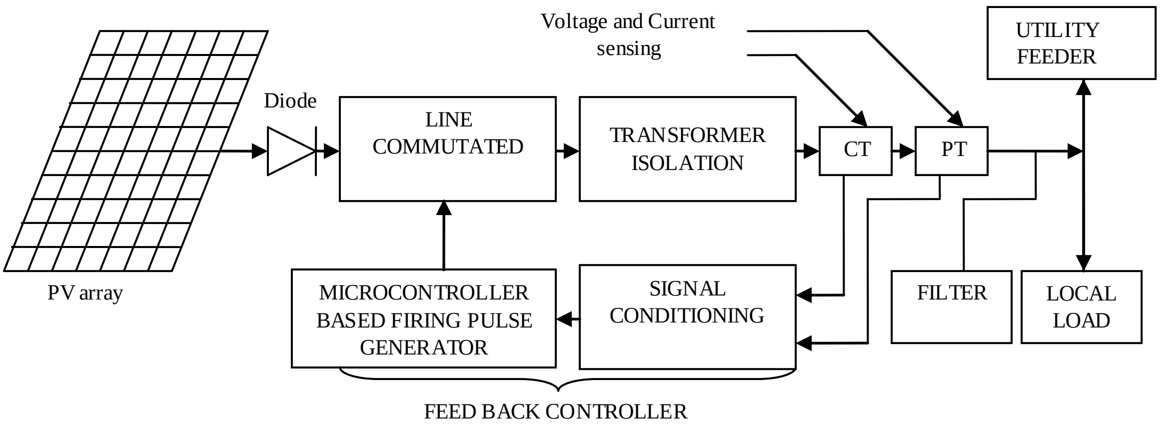


Fig. 1. The proposed PV system integrated with power grid using a feedback controller

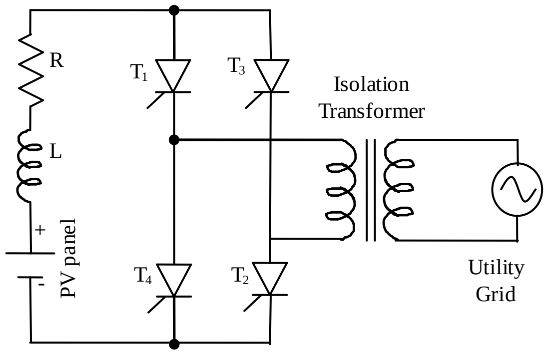


Fig. 2. The line commutated inverter

A. *Working of the closed loop scheme*

The circuit diagram of the multiplier along with the signal conditioning circuit is shown in Fig. 3. The multiplier receives voltage and current from the grid through PT and CT respectively. These signals are multiplied to give the output which has two components, a dc component and an ac component. The dc component corresponds to the real power delivered to the grid and the ac component varies with time, but at twice the frequency of input. So the output is filtered and the dc component is obtained. After passing through a buffer, this signal is amplified and added with a dc reference V_{max} to get the voltage corresponding to the firing angle for maximum power. The equations governing the analog multiplier in real power measurement are as follows [13].

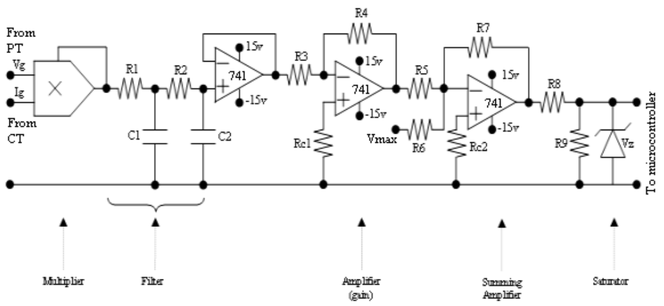


Fig. 3. Circuit diagram of the analog signal conditioning circuit

The multiplication of two sine waves of the same frequency, but of possibly different amplitudes and phases allow to double the frequency, and to directly measure the real power. Let the instantaneous values of the voltage and current applied to the multiplier be:

$$v = V_m \sin \omega t \quad (3)$$

$$i = I_m \sin(\omega t + \phi) \quad (4)$$

where ϕ = the phase difference between the two signals.

These signals when applied to the inputs of a four quadrant multiplier it will yield an output of:

$$v_{out} = \frac{V_m \sin \omega t . I_m \sin(\omega t + \phi)}{V_{ref}} \quad (5)$$

Expanding and grouping this equation will yield

$$v_{out} = \frac{V_m I_m}{2V_{ref}} \cos\phi + \frac{V_m I_m}{2V_{ref}} (\sin\phi \sin 2\omega t - \cos\phi \cos 2\omega t) \quad (6)$$

Equation 6 shows that the output from the multiplier has two terms. The first is a dc signal which is used for firing pulse generation by a microcontroller. The second term varies with time has no significance in the proposed work. Hence the desired signal is extracted and other is filtered by a second order filter. When the solar insolation changes the firing angle is adjusted by the microcontroller based on the dc signal magnitude to supply maximum power to the grid. Larger the dc signal magnitude, larger is the firing angle (α) variation and vice-versa. At the maximum power point (MPP), as the variation in dc signal is less, variation in α is less and at a point away from MPP, the variation in dc signal is large and hence variation in α is large. This introduces an adaptive step perturb and observe (P&O) MPPT technique for the proposed system [14].

B. *Minimization of Harmonics*

The ac output current of the inverter is a square wave and have large harmonic content. The output voltage of the inverter is sinusoidal as it is the grid supply voltage. Fourier analysis of the grid current gives the total harmonic distortion as [15].

$$THD = \sqrt{\left((I_{rms} / I_1)^2 - 1\right)} = 0.48 = 48\ \% \quad (7)$$

Hence, a filter is required to minimize the harmonics. There are several configurations in the filter design consisting of R, L and C components [16]. In the proposed work, a minimum cost conventional tuned filter is tuned to reduce third, fifth and seventh harmonic contents. One such combination connected across the single phase grid is shown in Fig. 4.

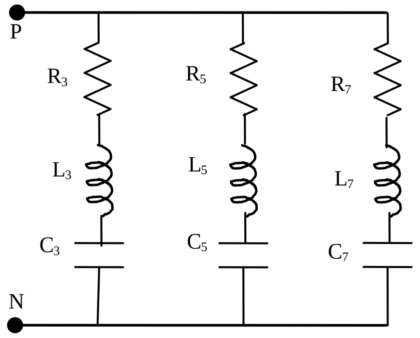


Fig. 4. LC tuned harmonic filter

There are three main considerations.

(i) The power loss in the resistor of each tuned filter should be as small as possible.

(ii) The harmonic currents should be reduced as much as possible without these currents flowing in to ac line.

(iii) The capacitor in the tuned filter has to supply a significant leading reactive VA that will partly compensate lagging VAR taken by the inverter.

Model of the Photovoltaic Cell

J. A. Gow and C. D. Manning [17], [18] proposed a model of PV cells for use with circuit-based simulation. To develop a complete solar PV power conversion system in simulation and to allow the interaction between a proposed converter and the PV array, it is necessary to develop a simulation model for a PV cell [19]. The equivalent circuit essentially consists of a current source shunted by a diode. These two elements correspond to generation and loss of photocurrent in the device. The resistances R_{sc} (series resistance of the PV array) and R_{sh} (shunt resistance) can be considered to be "parasitic" circuit elements, introduced to describe the behaviour of real solar cells with their technical limitations. S. Arul Daniel and N. Ammasai Gounden proposed a simulink model for PV arrays [20]. The classical equation of a PV cell describes the relationship between current I_{pv} and voltage V_{pv} of the cell (neglecting the current in the shunt resistance of the equivalent circuit of the cell) as

$$I_{pv} = I_{ph} - I_0\left[\exp\left(\frac{V_{pv} + R_{se}I_{pv}}{A}\right) - 1\right] \qquad (8)$$

Assuming

$$\exp\left(\frac{V_{pv} + R_{se}I_{pv}}{A}\right) >> 1, \quad \frac{I_0}{I_{sc}} \cong 10^{-9}$$

and $I_{ph} = I_{sc}$

Equation (8) can be written as

$$I_{pv} = I_{sc} - I_d \qquad (9)$$

where,

$$I_d = 10^{-9} I_{sc}\left(\exp\frac{20.7}{V_{oc}}(V_{pv} + R_{sc}I_{pv})\right) \qquad (10)$$

Since $V_{pv}|_{I_{pv=0}} = V_{oc}$, the above equations can be used to determine the characteristics of a panel or an array, as it is evident that the characteristics of a panel made up of identical cells can be obtained by appropriately scaling the characteristics of the individual cells. The parameters of the diode term are determined from the $V_{oc}(I_{sc})$ behaviour of the device. Neglecting the effect of the recombination losses in the i-layer, the analytical model yields the following expression:

$$V_{oc} = \left(\frac{nkT}{e}\right)\ln\left[\frac{I_{sc}}{I_o}\right] \qquad (11)$$

Equation (11) gives the voltage equation of the PV panel (an array of PV cells). Taking into account these equations, the simulink model of the PV cell is developed using MATLAB/SIMULINK.

Development of Control Scheme

For generating firing pulses to the SCRs, a microcontroller scheme is effectively used as it is more compact, requires less hardware and more reliable [21]. A low cost high performance PIC16F876 microcontroller [22] has been used for the control of the closed loop scheme. The microcontroller receives pulse from the zero crossing detector (ZCD) on pin 11 and generates pulses on pin 21 and 22 for the positive and negative conducting pairs of SCR respectively. The grid voltage is stepped down to 6 V and fed to the opamp ZCD circuit. The ZCD routine is written in such a way that both positive zero crossing and negative zero crossing of the input signal are sensed and firing pulses are generated for the corresponding pairs of SCRs. The firing pulses thus generated are fed to the gate circuit of the SCRs through a pulse amplifier circuit.

By varying the analog input to the ADC of PIC16F876 from 0 to 5V, the digital output of ADC is varied which in turn will vary the firing angle. In the proposed work, the analog input will vary between 3.6 V and 4.6 V. This analog input fed to the microcontroller from the signal conditioning circuit decides the range of firing angle (130^0 to 165^0) for maximum power extraction.

Closed Loop Scheme and Simulation Results

The complete MATLAB model of the closed loop scheme using simulink blocks in PSB platform is shown in Fig. 5 and the feedback controller is shown in Fig. 6. This consists of PV model, LCI, filter and the subsystem for generating the firing pulse to maximize the real power. The PV array model developed using the PV modelling approach discussed in section III is used for simulation in MATLAB/SIMULINK platform. The nominal voltage of the laboratory size PV panel used for the experiment on load is 12 V, and it's open circuit voltage and short circuit current are 21.2 V and 5.17 A respectively. The grid power is measured for different insolation on PV array.

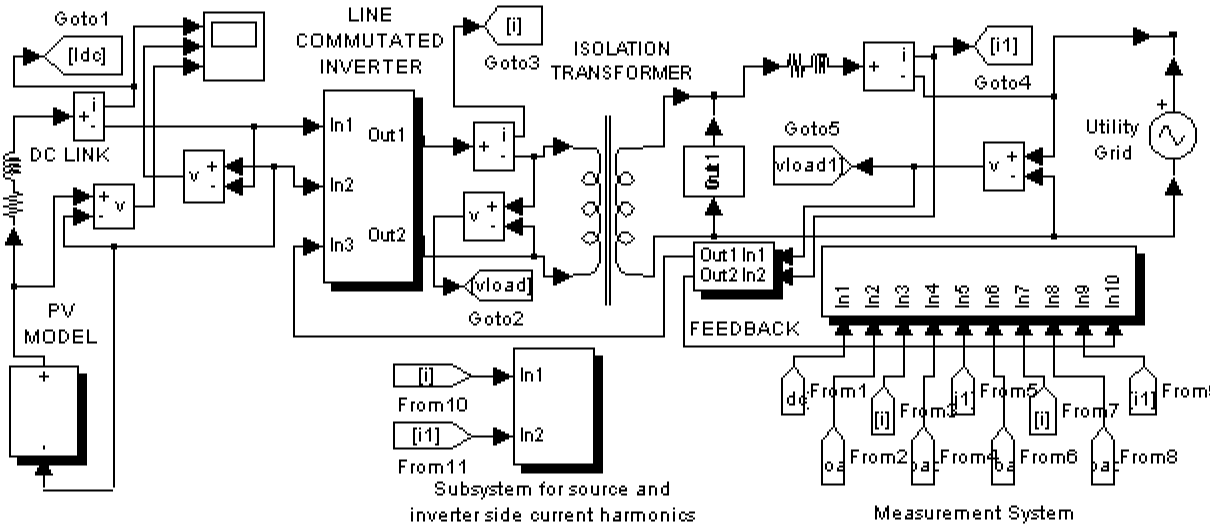


Fig. 5. Complete Simulink model of the proposed scheme.

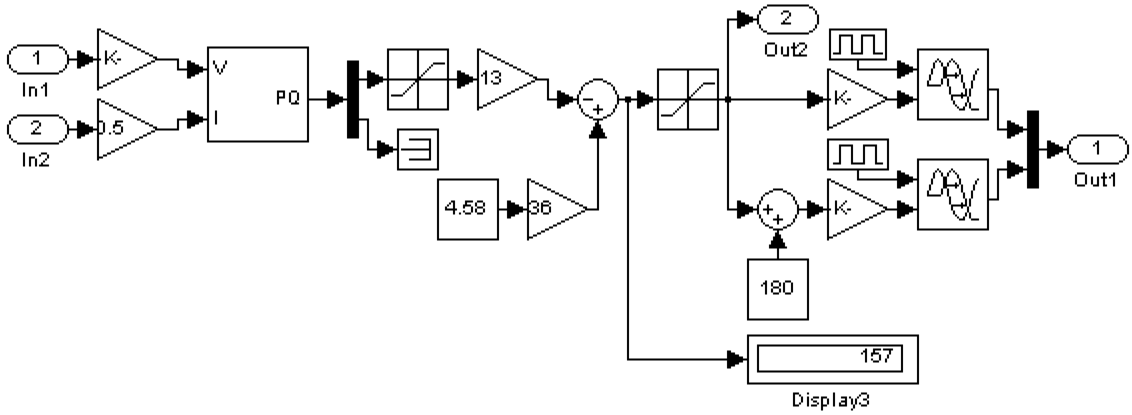


Fig. 6. Simulink model of the feedback controller.

LCI is a single phase thyristor converter fired at ωt = α and $\pi+\alpha$ respectively for alternate pairs of SCRs. Note that α is kept as more than 90^o for the converter to operate as inverter and the ac voltage of the inverter is connected to the grid through an appropriate single phase two winding transformer. The PV array is directly connected to the inverter through the dc link inductor. Appropriate gate firing pulses are applied for generating the firing delay angle and act as the feedback controller. The grid power is properly signal conditioned, and is used for firing the thyristors to deliver maximum power to grid. In simulation, the parameters are selected as per the experimental set up, which are as given below.

PV panel
Open circuit voltage = 21.2 V
Short circuit current = 5.17 A, rated power = 80 W
DC link inductor
R_{dc} = 0.232 Ω, L_{dc} = 3.4 mH
Isolation transformer
Capacity = 1 kVA, 24/240 V
R_{pri} = 0.3 p.u, R_{sec} = 0.8 p.u, X_{pri} = 0.03162 p.u, X_{sec} = 0.3162 p.u.

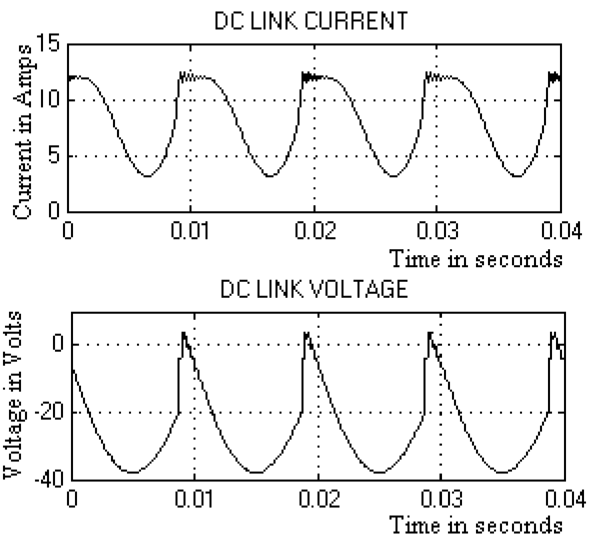


Fig. 7. DC link current and voltage when fired at 157^o shows the deviation in shape from its ideal shape.

Simulation is carried out using the developed model of the PV array and LCI using MATLAB/SIMULINK. Various results of simulation at $\alpha = 157^{o}$ are given in this section. The dc link voltage and current of the inverter are shown in Fig. 7. The waveforms corresponding to the voltage across and current through transformer primary and grid (secondary) are shown in Fig. 8. The transformer leakage inductance causes a small short circuit period when a pair of thyristors is fired and is clearly shown here. Fig. 9 shows the grid current waveform without filter and with harmonic filter. It shows that the grid current without filter is a square wave and that with filter is an approximate sine wave with reduced harmonics. The harmonic chart in Fig. 10 shows the harmonic contents in both the cases.

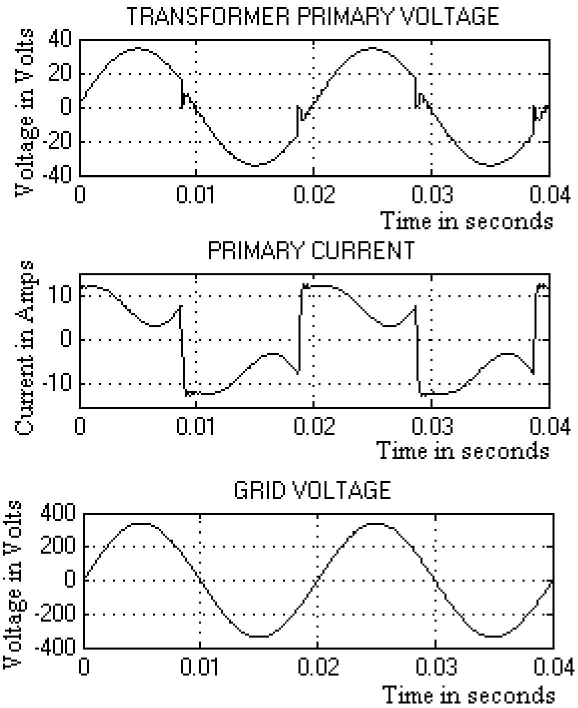


Fig. 8. Primary voltage showing the effect of transformer leakage inductance, primary current and grid voltage.

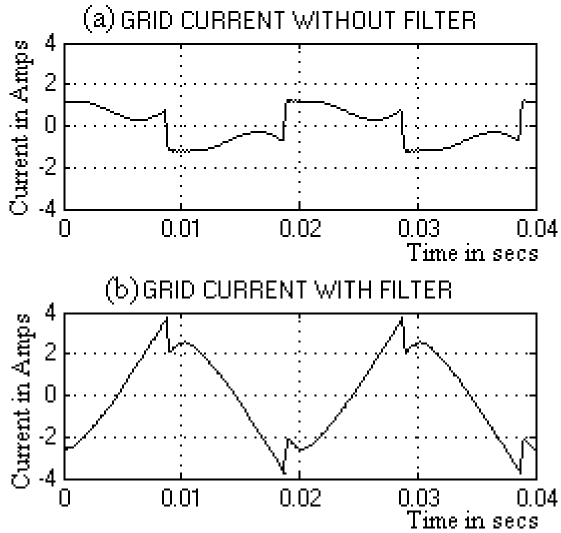
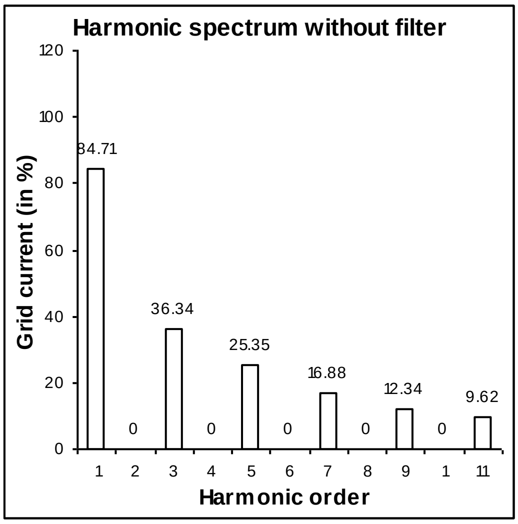
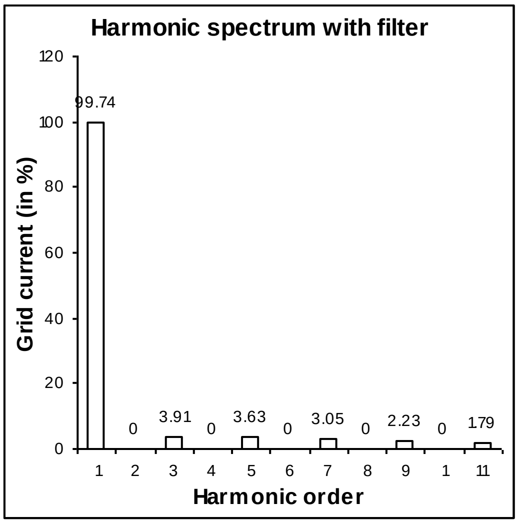


Fig. 9. Waveforms showing the grid current without and with filter



(a)



(b)

Fig. 10. (a) Harmonic spectrum of the grid current without filter (b) Harmonic spectrum of the grid current with filter.

Experimental verification

Experiments have been conducted with a solar PV array consisting of four panels with two series connected panels and two such parallel connected strings. The dc output from the PV array is fed to the utility grid through inverter and a two winding 24/240 V transformer. The controller for producing the firing pulses for the SCRs has been constructed using the PIC microcontroller together with an analog feedback circuit using Intersil's 8013 multiplier IC and 741 opamps. Depending upon the dc output of the PV array, the firing angle is automatically adjusted in the closed loop for extracting maximum power. A tuned filter is inserted between the grid and the inverter output for harmonic elimination.

The alternating current through transformer primary and secondary without filter is shown in Fig. 11. It is observed from the waveform of current that, it consists of considerable amount of harmonics. The waveform of grid current and voltage after placing the filter across the grid is shown in Fig. 12. The harmonic spectrum without and with filter is shown in

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Fig. 13 (a) and (b) respectively. It proves that the quality of grid current is improved.

For various insolation, the controller is tuned manually to feed maximum power to the grid. The variation of firing angle for a step increase in insolation, while tracking maximum power is shown in Fig. 14. The controller settling time is found as less as 50 milliseconds. Fig. 15 (a) and (b) show the comparison of simulated and experimental readings with open loop and closed loop controller respectively. The closeness of the closed loop results with the open loop results validates the working of both the hardware and software of the controller.

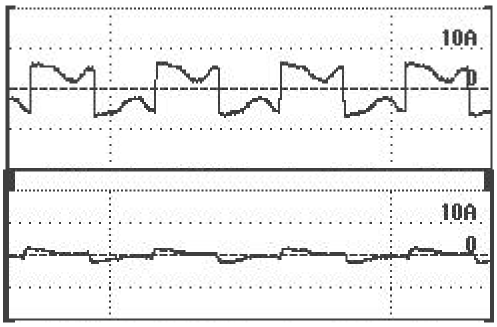


Fig. 11. Current through primary and secondary of the transformer without filter.

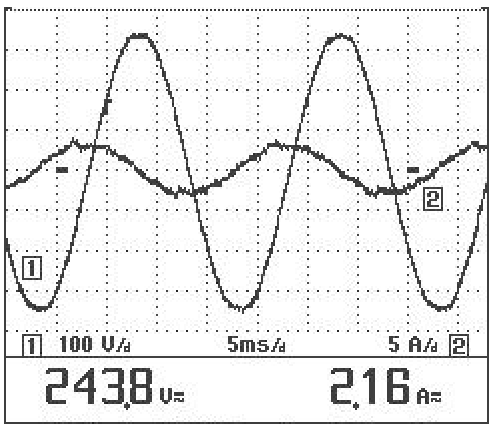
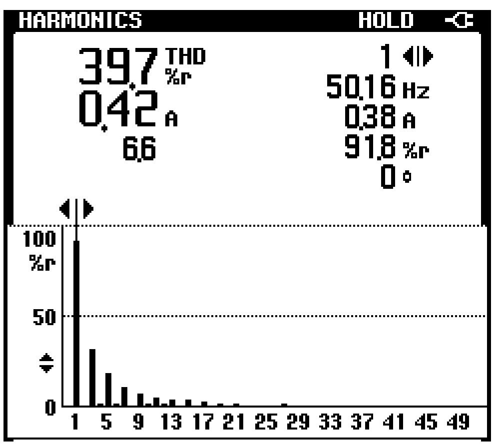
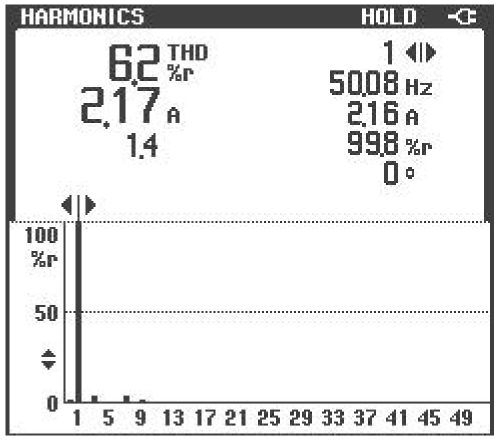


Fig. 12. Grid current and voltage with harmonic filter



(a)



(b)

Fig. 13. (a) Harmonic spectrum of the grid current without filter (b) Harmonic spectrum of the grid current with filter.

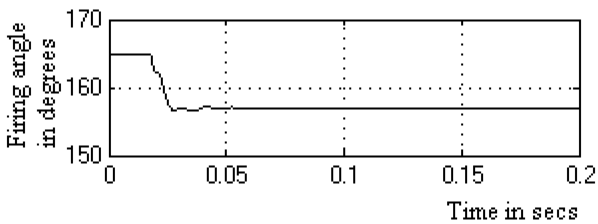
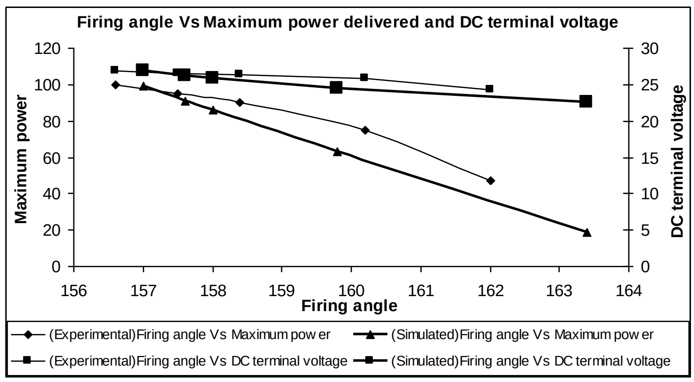
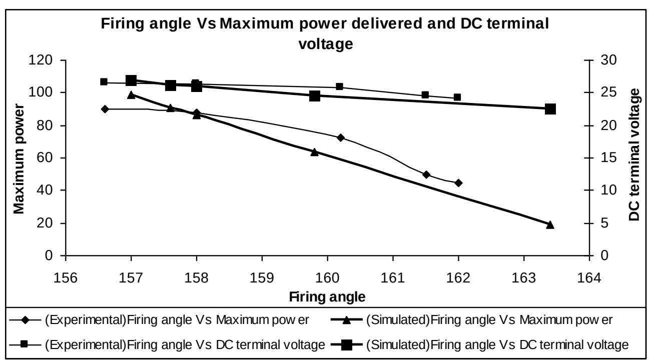


Fig. 14. Variation of firing angle for a step increase in insolation



(a)



(b)

Fig 15. (a) Simulated and experimental readings for open loop scheme. (b) Simulated and experimental readings for closed loop scheme.

Conclusions

The development of a simple maximum power tracking system for PV array is presented here. The closed loop scheme has been built in the laboratory and experiments were conducted on four pieces of 80 W panels arranged in required fashion. Experiments were conducted for different insolation on the PV array. The proposed system uses a closed loop control circuit which will fire the thyristors at the maximum power operating point. The control circuit for generating the firing pulses for the SCRs has been implemented using PIC16F876 microcontroller. The analog input corresponding to the required firing angle for maximum power is fed to the microcontroller for producing appropriate delay for the firing pulses to the thyristor. The closed loop controller has been designed from the knowledge of results obtained from the open loop system. It is observed that, the deviation in magnitudes of maximum power delivered in simulation and experiment in open loop and closed loop is very small. This clearly shows the efficacy of the developed closed loop scheme.

List of Symbols

I_{sc}	short circuit current of the PV array, A
V_{oc}	open circuit voltage, V
I_{mp}	maximum power PV current, A
V_{mp}	maximum power PV cell terminal voltage, V
R_{dc}	dc link resistance, Ω
L_{dc}	dc link inductance, mH
I_{dc}	current through dc link, A
v	instantaneous value of applied voltage to the multiplier, V
i	instantaneous value of applied current to the multiplier, A
ϕ	phase difference between v and i
V_{ref}	internal reference voltage of the multiplier, V
α	firing angle delay, degrees

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Biography

Binu Ben Jose D. R. was born in Kanyakumari, India, in 1976. He received the B.E. degree from Manonmaniam Sundaranar University and M.Tech. and Ph.D. degrees from National Institute of Technology, Trichy, India, in 1998, 2004 and 2015 respectively. He has thirteen years of teaching experience and one year of industrial experience. He is currently an Associate Professor with the School of Electrical Engineering, VIT University, Chennai campus, Chennai, India. His research interests are power electronic converters and its applications to Renewable Power Systems and optimization techniques applicable to Renewable Energy.