Performance Analysis of Grid Integrated PV System using SRF and IRPT Control

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***Abstract*—With the increase in grid connected PV based generation, degradation of power quality at the point of common coupling (PCC) has become a serious issue both for electric power utilities and consumers. Improvement in power quality is achieved through power factor correction, reactive power compensation and harmonic mitigation using different control techniques. This paper presents the performance analysis of grid integrated PV and addresses the power quality issues using synchronous reference frame (SRF) and instantaneous reactive power theory (IRPT) technique for inverter control. A 10 kW grid integrated photovoltaic system has been developed. Simulation of developed model is carried out on MATLAB/Simulink.**

Keywords—PV cell, Boost converter, SRF, IRPT, PFC, THD

I. INTRODUCTION

The increase in electrical energy demand and harmful environmental impact of conventional generation has speared growth of RES based power generation. Due to the integration of various renewable energy sources in the utility grids, power quality at the point of common coupling (PCC) degrades. The effect of degradation of power quality of electric power supply at consumer end are observed in form of harmonics, voltage sag, spikes, voltage swell, poor power factor and poor voltage regulation [1-4]. Harmonics are the index of the distortion level in the waveform of voltage and current. These are introduced in the system due to the presence of various power electronic devices and nonlinear loads in the system which draw nonlinear current from the source and are the main reason of harmonics generation. The problems associated with harmonics are overheating, failure of components, measurement errors etc. [5-6]

In this paper a 10 kW grid integrated PV based generating system is proposed, the PV inverter is controlled using two different techniques viz. SRF and IRPT for harmonic mitigation. These algorithms are simulated on MATLAB/Simulink environment. Both the algorithm will result in efficient operation of the PV based grid connected system.

II. PROPOSED SYSTEM

Fig. 1 depicts system configuration of grid interfaced PV system. The grid interfaced photovoltaic (PV) system consists of a solar PV array, converter for boosting the voltage level, three phase voltage source converter (VSC) and consumer loads. The system is two stage power conversion system. In the first stage, boost converter is used to convert the voltage that is obtained from PV array to the required voltage level. As power from PV array is not constant and changes with environmental conditions, therefore to track the

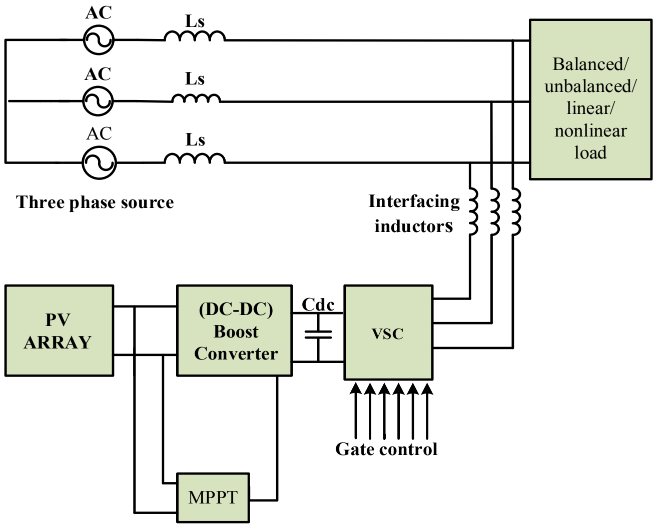

Fig.1 System configuration

maximum power, Perturb and observe MPPT algorithm is used. In second stage of conversion, dc link voltage obtained after first stage conversion is converted to ac voltage of required magnitude and frequency using VSC. VSC is an IGBT based three leg converter used to feed power to the load and utility grid. VSC serves the purpose of active and reactive power demand of load and maintain grid power factor at unity. Further in case of linear/nonlinear unbalanced loads on grid, VSC maintain the balancing of grid current by supplying current to linear/nonlinear loads thus eliminating the harmonics on the grid side for grid integration of PV system. synchronization of PCC voltage, current and frequency of the, grid with the PV system are required which is achieved using PLL.

III. MODELLING OF PV CELL

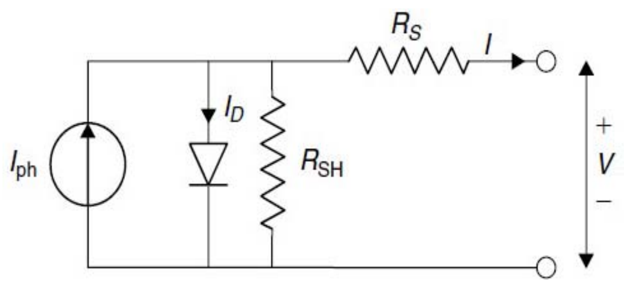

Fig. 2 Equivalent circuit of PV cell

Photo voltaic generator is neither a constant voltage source nor constant current source. A dc current is generated if solar irradiance falls on it. Approximate circuit of PV cell consist of current source (I_{ph}), diode, shunt (R_{sh}) and series

(R_s) resistance. Fig. 2 depicts the approximate equivalent circuit of PV cell from which nonlinear characteristics can be derived. Depending on the application, required voltage and power level can be derived from the PV cell by connecting them in series or parallel combination and forming a PV array. The PV cell can be presented by Eq. 1 to 3:

$$I_D = I_S\left[e^{\left(q\left(\frac{V+IR_S}{KT}\right)\right)} - 1\right]$$

(1)

Output current of solar cell:

$$I = I_{ph} - I_D - I_{sh}$$

(2)

By putting the value of I_D and I_{ph} in the above Eq. 2, output current Eq. can be written as:

$$I = I_{ph} - I_S\left[e^{\left(q\left(\frac{V+IR_S}{KT}\right)\right)} - 1\right] - (V + IR_S)/R_{sh} \qquad (3)$$

Where I is output current (A), I_D is current through the diode, I_{ph} is photon current generated by PV cell, V is output voltage (V), I_S is saturation current, q is electron charge ($1.6 * 10^{-16}\ C$), K is Boltzmann constant ($1.381 * 10^{-23}\ \frac{J}{K}$) and T is operating temperature (K), R_{sh} is shunt resistance and R_s is series resistance.

By considering above equations and using series and parallel combination of cells, a 10 kW PV array has been developed and simulated in MATLAB/ Simulink environment.

IV. I-V and P-V Characteristics of the PV Array and MPPT

Fig. 3 and 4 depicts the current-voltage and power-voltage characteristics of the solar array at different solar insolation and operating temperature respectively. Output power of the photovoltaic array is calculated by multiplying voltage across entire array and total current corresponding to the entire configuration. Current and voltage corresponding to maximum power point is located and noted from I-V and P-V curve respectively.

As the characteristics of the PV array is continuously varying due to varying temperature and irradiance so the maximum power point (MPP) must be tracked with proper speed and accuracy for the efficient performance of the PV array. This can be achieved using different algorithms. In this paper perturb and observe algorithm is used to track MPP. A dc-dc converter is connected between inverter and source PV interface the MPPT. By varying the on/off time of the converter switch, impedances seen by the source is matched with load to transfer the maximum possible power to load at that available environmental conditions. Thus MPPT algorithm keeps solar PV operating point corresponding to maximum power.

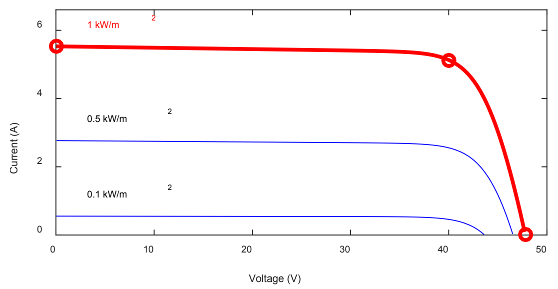

Fig. 3(a) I-V curve of one module at variable insolation

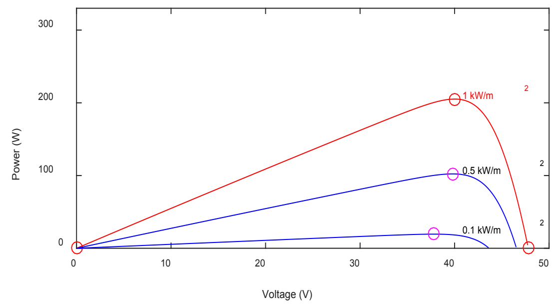

Fig. 3(b) P-V curve of one module at variable insolation

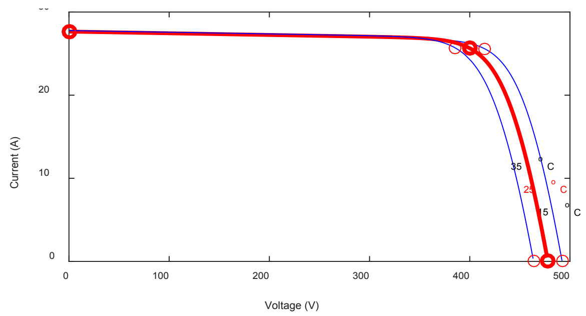

Fig. 4(a) I-V curve of array at variable temperature

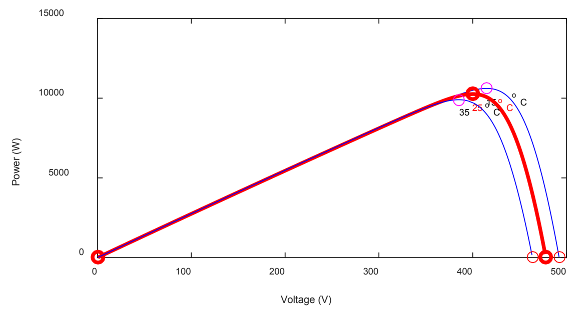

Fig. 4(b) P-V curve of array at variable temperature

V. Design of Converter System Parameters

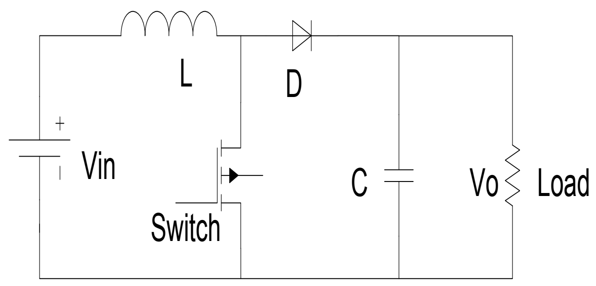

Fig. 5 Schematic diagram of Boost converter

Fig.5 depicts the boost converter (dc-dc) having output voltage more than its input voltage. The output voltage and current equations for above converter are given below [7]:

$$V_O = V_{in}/(1-K) \quad (4)$$

$$I_O = I_{in}/(1-K) \quad (5)$$

$$L = K*(1-K)*R_o/(2*f_{sw}) \quad (6)$$

L=0.4133∗(1-0.4133)/ (2∗10000) = 0.72 mH.

$C = K/(2*f_{sw}*R_o)$ = 350 μF, $f_{sw} = 10\ kHz$

Where K is duty ratio and R_o is load resistance, V_O is output voltage, I_O is output current, f_{sw} is switching frequency, L and C are the inductance and capacitance of the boost converter respectively.

A. DC link Voltage

Minimum required voltage across dc link capacitor must be more than two times of the voltage per phase of the system [8].

$$V_{dc} = 2\sqrt{2}*V_{LL}/(\sqrt{3}*m) \quad (7)$$

V_{dc}= (2√2) *415 / (√3*0.95)

Modulation index (m) is taken as 0.95. Voltage across dc link obtained from Eq. (7) is 713V for V_{LL} of 415 V and is chosen as 750V.

B. Rating of DC link capacitor on the basis of Ripple

$$C_{dc} = (P_{dc}/V_{dc})/(2*314*V_{dcripple}) \quad (8)$$

Where C_{dc} is dc link capacitor, V_{dc} and P_{dc} are dc link voltage and power respectively. Considering $V_{dcripple}$ as 3% of V_{dc} , P_{dc} as 10 kW and V_{dc} as 750 V.

C_{dc}= 943.61 μF

Selected value of C_{dc} is 1000 μF.

C. Rating of Interfacing inductor of VSC

Interfacing inductor rating of VSC depends on switching frequency (f_{sw}), current ripple (Δi) and dc link voltage (V_{dc}). Interfacing inductor (L_f) is given as follows:

$$L_f = \sqrt{3}*m*\ V_{dc}/(12*h*f_{sw}*\Delta i) \quad (9)$$

$L_f = 6.78\ mH$

Where h is overloading factor, m is modulation index and Δi is current ripple. Assuming, $m = 1, V_{dc} = 750\ V, h = 1.2, f_{sw} = 10\ kHz\ and\ \Delta i = 10\%$.

The calculated value of L_f is 6.78 mH. In the proposed system L_f of 7 mH is taken.

Table I shows the system parameters considered in this system.

TABLE I SYSTEM PARAMETERS

Design parameter of boost converter	Values	Unit
Inductor (L)	0.72	mH
Capacitor (C)	1000	μF
Switchign frequency (fsw)	10	kHz
Input voltage	440	V
Output voltage	750	V
Duty cycle	41.33	%
Interfacing inductor(Lf)	7	mH

Design parameter of boost converter	Values	Unit
Source or Grid voltage	415	V

VI. Inverter Control Algorithms

A. SRF Theory of Inverter Control

Fig. 6 represents the block diagram of inverter control algorithm using SRF theory. SRF theory or d-q theory uses Park's transformation to convert load current components from synchronous reference frame to d-q reference frame. This algorithm consist of two PI controllers, one is used to maintain the voltage across dc link and the second controller is used to maintain PCC voltage constant and stable. Low pass filter is connected to extract the fundamental quantities (i_d and i_q) of the load current. To operate the grid on unity power factor, inverter must supply the reactive power demand of the load and should be operated under power factor correction mode (UPF) i.e. $i*_q$ must be zero ($i*_q$ =0, $i*_{q=}$ $-i_q + i_{qr}$) and $i*_d$ is added with i_{loss} component so as to maintain the dc link voltage constant. Converting these reference signals from d-q frame to synchronous reference frame using inverse parks transformation, reference signals (i_{sa}, i_{sb}, i_{sc}) obtained from control algorithm, are compared with sensed grid current ($i*_{sa}$, $i*_{sb}$, $i*_{sc}$) using hysteresis control and generate gate signals to operate inverter on UPF mode.[8-12]

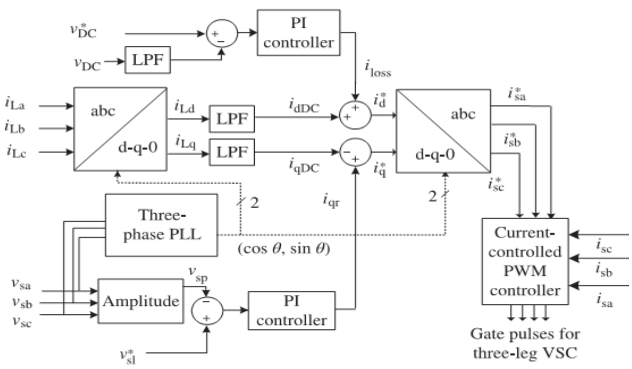

Fig. 6 Inverter control algorithm using SRF theory

B. IRPT Theory of Inverter Control

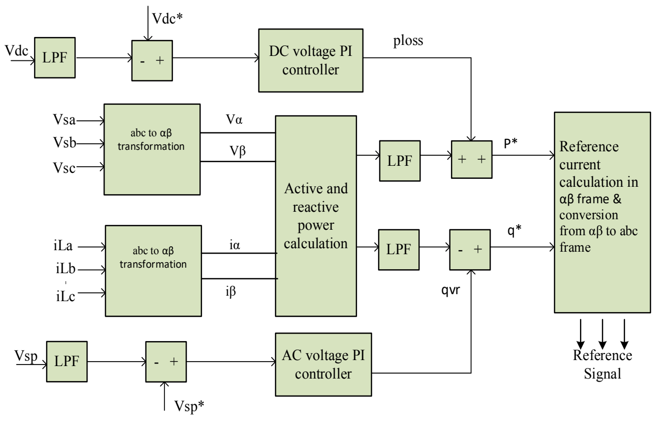

Fig. 7 Inverter control algorithm using IRPT

Fig. 7 depicts the block diagram representation of IRPT inverter control theory. In this theory Clark's transformations are used to converts the load current and PCC voltages in to α-β frame. Instantaneous value of active and reactive power are estimated by using the equations of active and reactive power. Estimated power consist of both dc and ac component. To extract the fundamental components, low pass filters are used. Reference value of both the power (p* and q*) is estimated using Eq. given below:

$$p^* = p_{dc} + p_{loss} \quad (10)$$

VII. Model of Grid integrated Photovoltaic System

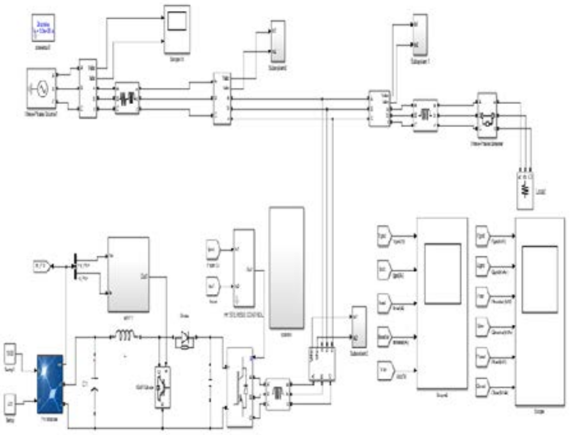

Fig. 8 Developed model of Grid integrated PV system

Fig. 8 represent Simulink model of 10 kW grid connected PV system. Control of dc link voltage and PCC voltage are achieved using PI controllers. The system is operated under UPF mode to supply the load reactive power demand by inverter and to maintain the unity power factor on grid side.

VIII. Results and Discussions

To study the performance of developed control algorithms, linear and nonlinear loads of 5kW and (R=100 Ω, L=100 H) are taken respectively. The system is assumed to be working at standard test condition. Performance analysis of entire system is done in PFC mode, for both linear and nonlinear loads. Further to impose the unbalanced load condition on the system, one phase is kept open from 0.3 to 0.5 second. Entire simulation is carried out in MATLAB Simulink.

$$q^* = q_{vr} - q_{dc} \quad (11)$$

In power factor correction mode q* must be zero to maintain the unity power factor of the grid. Reference p* and q* are converted in to α-β frame. Taking the inverse Clark's transformation will give reference signal (i_{sa}, i_{sb}, i_{sc}). Reference signals (i_{sa}, i_{sb}, i_{sc}) obtained from control algorithm are compared with sensed grid current (i^*_{sa}, i^*_{sb} ,i^*_{sc}) using hysteresis control and generate gate signal to operate the inverter at unity power factor mode. [13-15]

A. SRF Algorithm of Inverter Control

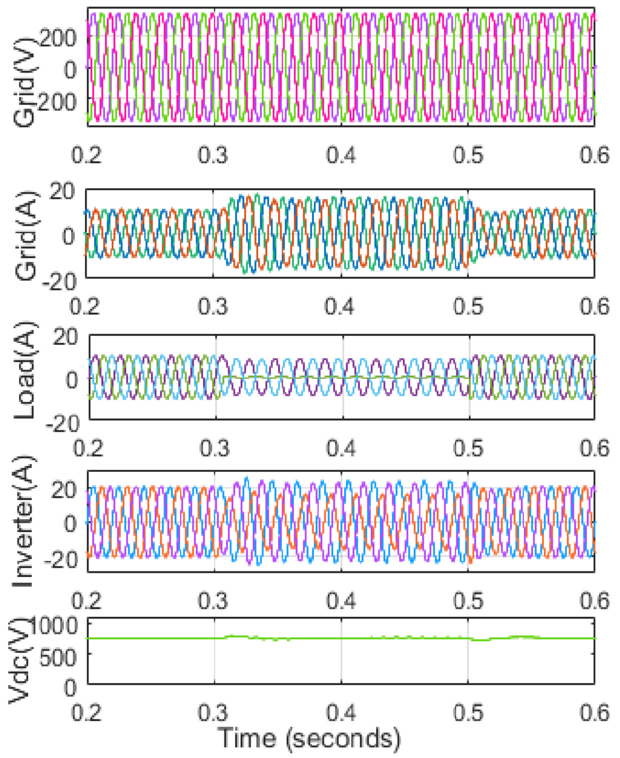

Fig. 9 Performance analysis of inverter control using SRF theory in PFC mode for linear unbalanced load

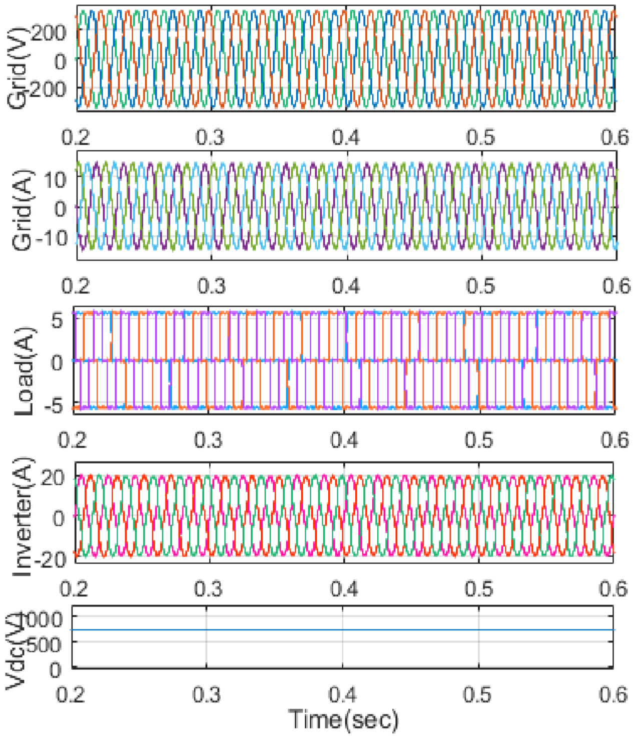

Fig. 10 Performance analysis of inverter control using SRF theory in PFC mode for nonlinear load

Fig. 9 and 10 shows the voltage at point of common coupling (Grid(V)), grid current (Grid(A)) load current (Load(A)) and inverter current (Inverter(A). It has been observed that even during unbalanced loading or single phasing, grid voltage and current are balanced. Inverter supplies the reactive power demand of load and grid operation is maintained at unity power factor.

B. *IRPT Algorithm of Inverter Control*

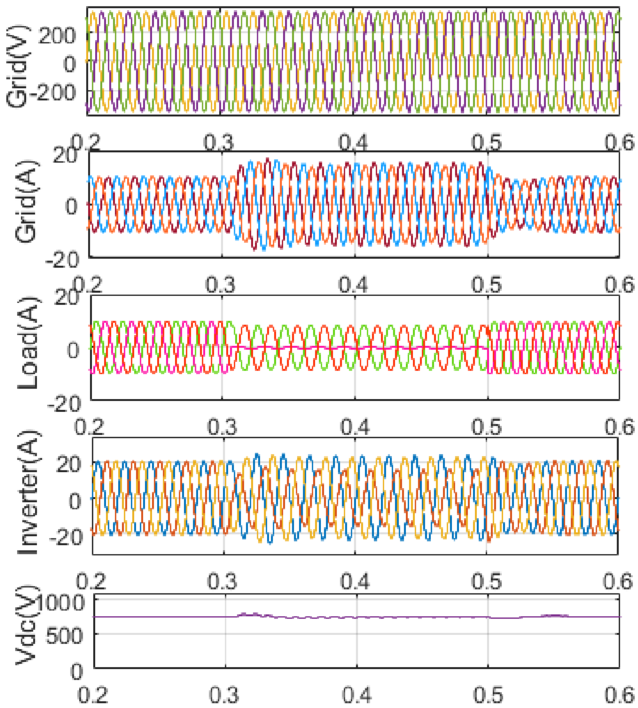

Fig. 11 Performance analysis of inverter control using IRPT theory in PFC mode for linear unbalanced load

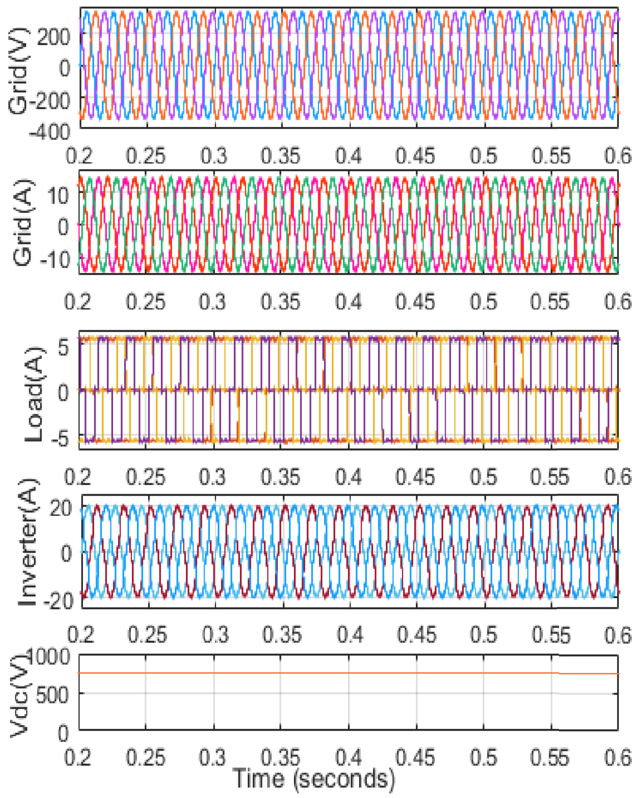

Fig. 12 Performance analysis of inverter control using IRPT theory in PFC mode for nonlinear unbalanced load

Fig. 11and 12 shows the performance waveform of inverter control using IRPT theory in the MATLAB simulation environment for PFC mode. From fig. 11 and 12, it can be observed that for unbalanced linear and nonlinear loads, grid current are balanced. Also grid current are in phase, validating the UPF mode of inverter operation.

C. *Estimation of Total Harmonic Distortion*

Percentage (%) total harmonic distortion (THD) is estimated for different parameters like PCC voltage and grid current of grid integrated PV system for nonlinear loads, when SRF and IRPT theory for inverter control algorithms are employed. Fig. 13 shows the THD of load current for nonlinear load. Fig. 14 and 15 represent the FFT analysis of grid voltage and grid current respectively using SRFT and IRPT control techniques. Table II depicts the percentage THD for inverter control algorithm in unity power factor mode of operation. It has been observed that SRF control technique gives better response for nonlinear load.

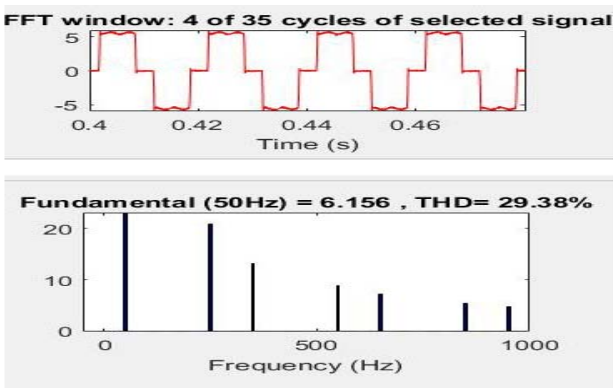

Fig.13 THD of load current for nonlinear load

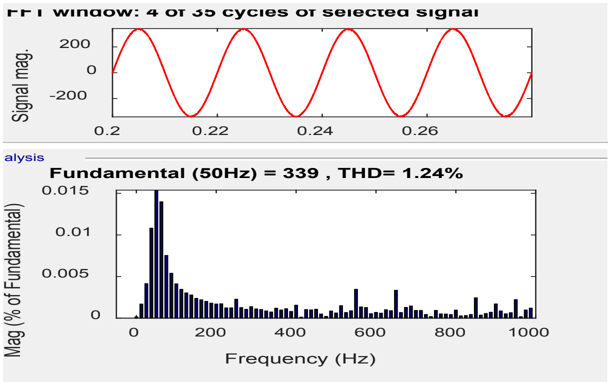

Fig.14 (a) THD of grid voltage (V) for nonlinear load using SRF control

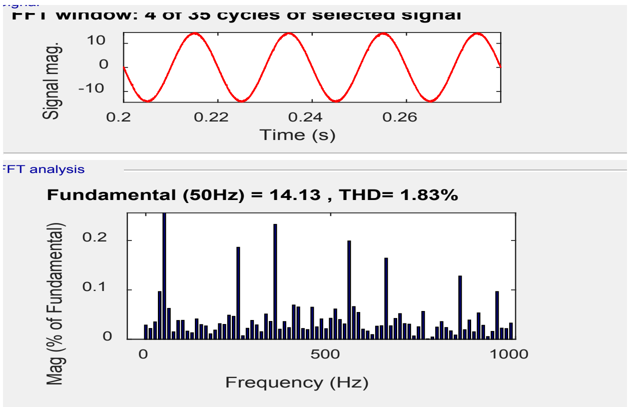

Fig.14 (b) THD of grid voltage (V) for nonlinear load using IRPT control

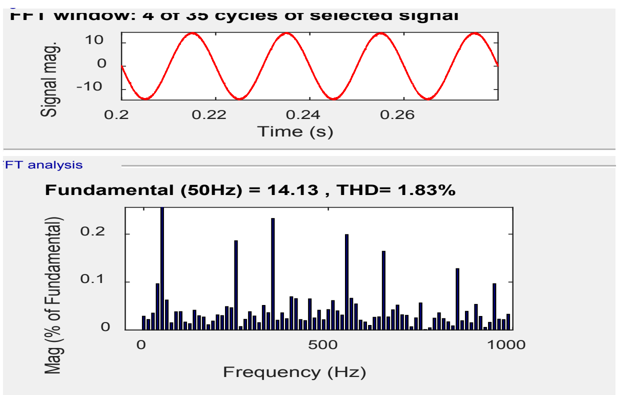

Fig.15 (a) THD of grid current for nonlinear load using SRF control

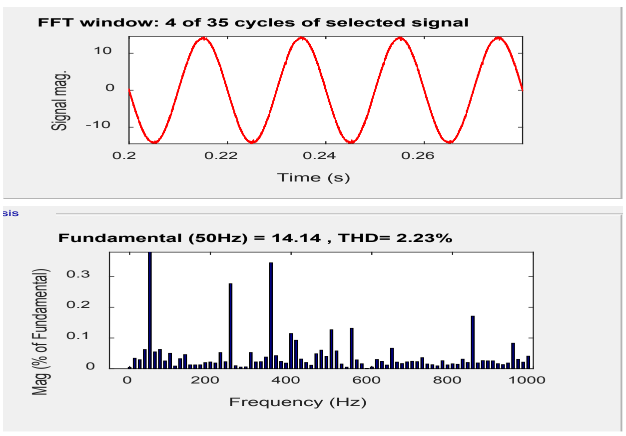

Fig. 15(b) THD of Grid current for nonlinear load using IRPT control

TABLE II % THD VALUES FOR DIFFERENT SYSTEM PARAMETER

Different parameter of system	Percentage (%) THD value	
	SRF(nonlinear load)	*IRPT(nonlinear load)*
Grid voltage (Grid(V))	1.24	1.83
Grid current (Grid(A))	1.83	2.23
Load current (Load(A))	29.38	29.38

IX. CONCLUSION

In this paper a 10 kW, grid integrated PV system has been designed and developed. Simulation of developed model has been carried out in the environment of MATLAB-SIMULINK. SRF and IRPT control algorithms are employed and system performance has been investigated.
It has been observed that both the control algorithms give efficient performance under different linear and nonlinear load conditions. THD on grid side current is well within IEEE standard IEC61727 i.e. below 5 % and UPF operation has been maintained.

References

[1] Arun kumar verma,Bhim singh, D.T.Shahani"Grid interfaced solar photovoltaic power generating system with power quality improvement at ac mains," IEEE ICSET 2012, Nepal.

[2] Sanjay Kumar; Arun Kumar Verma; Ikhlaq Hussain; Bhim Singh," Performance of Grid Interfaced Solar PV System under Variable Solar Intensity,"2014 IEEE 6th India International Conference on Power Electronics (IICPE),8-10 Dec. 2014.

[3] E.Wald F.Fuchs, Mohammad A.S.Masoum "Power Quality in Power Systems and Electrical Machines," Academic press is an imprint of Elsevier, 2008.

[4] IEEE Working Group on Power System Harmonics "Power System Harmonics: An Overview," IEEE Power Engineering Review, Vol.3, No.8, pp. 27-28, Aug-1983.

[5] Yash P. Bhatt and Mihir C. Shah," Design, Analysis and Simulation of Synchronous Reference Frame based Phase Lock Loop for Grid Connected Inverter" 1st IEEE International Conference on Power Electronics. Intelligent Control and Energy Systems (ICPEICES-2016).

[6] W.M.Grady, M.J.Samotyj and A.H.Noyola "Survey of Active Power Line Conditioning Methodologies," IEEE Trans on Power Delivery, Vol.5, No.3, pp. 1536-1542, July-1990.

[7] S. Kolsi1*, H. Samet2, M. Ben Amar,"Design Analysis of DC-DC Converters Connected to a Photovoltaic Generator and Controlled by MPPT for Optimal Energy Transfer throughout a Clear Day", Journal of Power and Energy Engineering, 2014, 2, 27-34 Published Online January,2014,(http://www.scirp.org/journal/jpee),http://dx.doi.org/10. 4236/jpee.2014.21004

[8] Bhim Singh,Ambrish Chandra, Kamal Al-Haddad," Power quality problems and mitigations "@2015 John Wiley and Sons Ltd.

[9] X.-Q. Guo, W.-Y. Wu, and H.-R. Gu, "Phase locked loop and synchronization methods for grid-interfaced converters: a review," Przegląd Elektrotechniczny (Electrical review), vol. 4, pp. 184-187, 2011.

[10] Mr. Shantanu Chatterjee,Dr. Saibal Chatterjee," Simulation of Synchronous Reference Frame PLL based Grid Connected Inverter for Photovoltaic Application"ICPDEN2015.

[11] Mateus F Schonardie and Denizar C Martins, ―Application of the dq0 transformation in the three phase grids connected PV system with active and reactive power control,‖ Power Electronics Specialists Conference. pp. 1202 – 1208, June 2008.

[12] Nikita Gupta, Rachana Garg, "Characterization Study of PV module Connected to Microgrid" IEEE INDICON 2015 1570177081.

[13] H. Akagi, Y. Kanazawa, and A. Nabae, "Instantaneous Reactive Power Compensators Comprising Switching Devices without Energy Storage Components," Industry Applications, IEEE Transactions on , vol.IA-20, no.3, pp.625-630, May 1984.

[14] G. Adamidis and G. Tsengenes, ―Three phase grid connected photovoltaic system with active and reactive power control using instantaneous reactive power theory,‖ International Conference on Renewable Energies and Power Quality, pp. 8 – 16, March 2010.

[15] Ariya Sangwongwanich , Yongheng Yang, Dezso Sera, Hamid Soltani and Frede Blaabjerg,"Analysis and modeling of interharmonics from grid connected photovoltaic systems," IEEE Transactions on Power Electronics, vol. 33, no. 10, pp. 8353-64,October 2018.