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Dynamic Simulation of Grid Tied PV-Inverter Under Distorted Grid Voltage

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Abstract: This paper presents a control strategy for a grid interface system fed by a PV source. A two stage topology with boost converter followed by a three phase VSI (voltage source Inverter) is employed for the grid interface. The proposed control strategy is capable of injecting harmonic free current to the grid even when the grid voltage is highly distorted. Also it is ensured maximum power is extracted from the PV and injected to the grid. The design of the magnetics used in the grid interface is also presented. The proposed control scheme is validated for injecting real power to the grid from a PV source by simulation in MATLAB SIMULINK environment. The results show that the proposed control scheme is an attractive solution for grid interface of DG sources like PV, fuel cells and wind driven PMSG.

Keywords: Photo-voltaic array, Three phase inverter, PLL, Hysteresis controller, d-q reference frame.

I. INTRODUCTION

In grid connected PV fed inverter, there are several topologies to inject PV generated power into the grid. Output of the PV system is fluctuated due to variation in solar irradiance. Fluctuation in output power cause interconnection point power flow fluctuation. In order to minimize interconnection point power flow fluctuation the smart grid technique is utilized [1].

The energy generated by a PV system is not coinciding with residential energy demand. There may be electricity spillage at daytime when the PV electricity generation is high and electricity shortage at night time when the PV electricity generation is low. To avoid this mismatch, battery may have to be used. By storing some excessive generated electricity at day time, it can be released at night time to supplement the power usage for a household [2].

Active power from PV solar farm is distributed to grid through the Power Conditioning System (PCS). PCS consist of chopper and inverter. During conversion process switching harmonics are present in the inverter. It causes synchronization problem in grid. In order to avoid switching harmonics, LCL filter is introduced in the output of the inverter which is used to filter the harmonics in the output of the inverter [3]. Composite Energy Storage System (CESS) consists of chopper which is connected at the output of the battery and ultra-capacitor.

In high power application, large number of battery is used. So, we have to provide same number of chopper at its output terminal. Utilization of large number of battery with chopper causes the volumetric efficiency of the system [4].

The inverter controls the active power flow from the energy source to the grid and also performs the compensation of reactive power and the nonlinear load current harmonics, keeping the grid current almost sinusoidal [5]. The extraction of fundamental component of grid voltage and harmonic compensation is done by adaptive filter network [6].

A proportional–resonant (PR) controller introduces an infinite gain at a selected resonant frequency to eliminate steady-state error or current harmonic at that frequency. The weighted average value of the currents flowing through the two inductors of the LCL filter is used as the feedback to the current PR regulator. The disadvantage mainly lies in the oscillatory nature of the control, which makes it suitable only for those applications where it can be used alone [7].

Schemes based on one-cycle control (OCC) which do not require the service of a phase-locked loop for interfacing the inverter to the grid. OCC maintain inverter output current proportional and in-phase with grid voltage. OCC-based schemes exhibit instability in operation [8]. Converter circuit is a main reason for harmonics due to its nonlinear load. Here harmonic compensation is done by virtual impedance based control of the grid interfacing inverters [9].

In proposed scheme, PV array is tied with grid through three phase Voltage source Inverter (VSI). Boost converter is placed between PV array and inverter. The maximum power in PV array is tracked using P&O based MPPT controller. The MPPT controller controls duty cycle of the boost converter IGBT. The fundamental component of the grid voltage is extracted using PQ theory.

PLL is used to get the phase and frequency information of grid voltage. Hysteresis current controller is used to generate PWM signal by comparing actual and reference current. The PWM signal controls the gate terminal of the inverter's IGBT.

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The rest of the paper organized as follows: Section II discuss the description of the system, Section III explains the control strategy for grid connected PV array fed inverter, Section IV explains the design of interfacing inductance and Section V explains the simulation of grid connected PV array fed inverter.

II. DESCRIPTION OF SYSTEM

When light shines on a solar cell, photovoltage is generated. The generated voltage across the solar cell can drive the current in an external circuit and therefore, can deliver power. In order to collect the energy of a photon in the form of electrical energy through solar cell, the following series of actions should take place: (a) Increase in the potential energy of carriers, (b) Separation of carriers.

Among these, task (a) is performed efficiently by a semiconductor material. Semiconductor material possesses energy levels separated from each other. On absorption of a photon, the difference in energy level results in an increase in the potential energy of electrons, and also keeps the excited electrons in the higher energy level for a longer period than its relaxation time to the ground state in the valence band. This increases the probability of charge separation and extraction of work from the device.

In order to perform task (b), separation of charge carriers, asymmetry in the semiconductor device is required. Asymmetry should be such that the generated electron-hole pairs should get separated from each other. Combination of P-type semiconductor and an N-type has such asymmetry which provides a built-in electric field at the junction. When light shines on a solar cell, a large number of electron hole pairs are created. Due to asymmetry in the P-N junction, the generated electrons tend to flow from N-side to P-side, resulting in the separation of the charge carriers which can flow in the external circuit delivering the work to the load. In this way, use of P-N junction makes it possible to convert light energy into electrical energy [10].

Solar PV generates direct current electricity from solar insolation. However, the grid connected application requires that the DC is converted into AC before the power can be fed into the grid. In proposed scheme three phase Voltage Source Inverter (VSI) is used to convert PV-DC power to AC power.

Whenever a solar PV module is used in a system, its operating point is decided by the load to which it is connected. Also since solar radiation falling on a PV module varies throughout the day, the operating point of module also changes throughout the day. To extract maximum power from the PV array, a DC-DC converter is used between PV array and the inverter. Here boost type DC-DC converter is used to provide output voltage greater than the PV source voltage.

The duty cycle of the boost converter is controlled to impose optimum voltage across the PV array which corresponds to Maximum Power Point (MPP). The maximum power tracking mechanism makes use of an algorithm and an electronic circuitry. The mechanism is based on the principle of impedance matching between load and PV module, which is necessary for maximum power transfer. The impedance matching is done by changing the duty cycle of the boost converter. The reactive power is essential for creating the needed coupling fields for energy devices. The most significant part of the voltage drop in the line reactance is due to the variation in consumption of grid current. The reactive component in the line current is eliminated by series compensated network. In grid connected system series inductor is used as static Var compensator. The series inductor draw lagging current and it is also known as absorbers of reactive power.

The control scheme applied for inverter control having four stages. In first stage, Phase Locke Loop (PLL) is used to get the phase and frequency information of grid voltage. PLL keeps an output signal synchronized with a reference input signal in frequency and phase. In second stage PQ theory also known as park transformation is used to extract the fundamental component of the grid voltage. The fundamental component of the grid voltage is called as reference voltage. In third stage, the reference current algorithm generates reference current for desired power injection. In fourth stage, hysteresis current control technique is used to generate pulse width modulated (PWM) signal by comparing reference current and actual grid current. The PWM output of the hysteresis controller is the gate signal for inverter's IGBT gate terminal. Fig.1 shows the block diagram of grid connected PV array fed inverter.

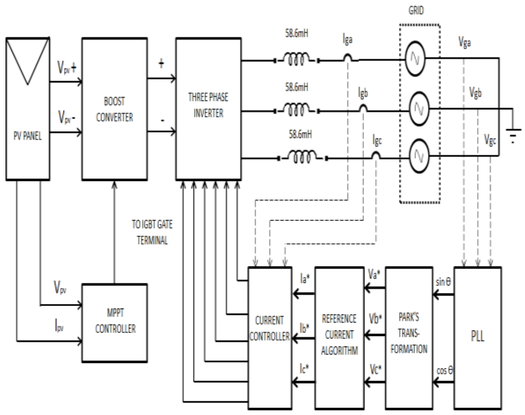

Fig.1. Block diagram of grid connected PV array fed inverter.

III. CONTROL STRATEGY FOR GRID CONNECTED PV ARRAY FED INVERTER

In this section control technique applied for grid connected PV array fed inverter has been discussed in following four stages.

- MPPT controller.
- Park transformation with PLL.
- Reference current generation.
- Hysteresis current controller.

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A. MPPT Controller(P&O Algorithm)

Algorithms for MPPT are various types of schemes that are implemented for obtaining maximum power transfer. Some of the popular schemes are the hill climbing method, incremental conductance method, constant voltage method, modified hill climbing method, system oscillation method and the ripple correlation method. Energy extracted from the PV source through MPPT should be either utilized by a load or stored in some form. In view of this, grid connected PV systems are very popular as they do not have any storage requirement since the grid can absorb any amount of PV energy tracked.

The most popular algorithm is the hill climbing method also known as Perturb & Observe (P&O) method. In proposed scheme it is applied by perturbing the duty cycle'*d*' at regular intervals and by recording the resulting array current and voltage values, thereby obtaining the power. Once the power is known, a check for the slope of the PV curve or the operating region is carried out and then the change in'*d*' is effected in a direction so that the operating point approaches MPP on the power-voltage characteristic. The algorithm of this scheme is described below along with the help of mathematical expressions (1) to (3). Fig.2 shows the flowchart of the P&O algorithm.

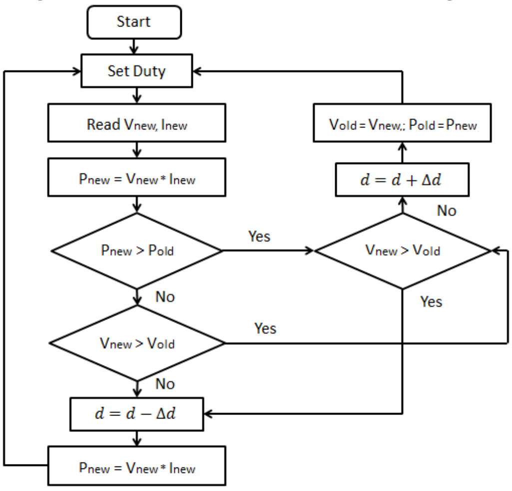

Fig.2. Flowchart for P&O based MPPT algorithm.

In the voltage source region,

$$\frac{\partial P_{PV}}{\partial V_{PV}} > 0 \Rightarrow d = d + \Delta d; \qquad (1)$$

In the current source region,

$$\frac{\partial P_{PV}}{\partial V_{PV}} < 0 \Rightarrow d = d - \Delta d; \qquad (2)$$

At MPP,

$$\frac{\partial P_{PV}}{\partial V_{PV}} = 0 \Rightarrow d = d; (or) \Delta d = 0; \qquad (3)$$

B. Park Transformation with PLL

In park transformation fundamental component of the grid voltage is extracted in three stages. In first stage, time varying grid voltage (Vg***abc***) is converted into time in-variant voltage (Vdq0) through abc-dq0 transformation block. Equation (4) to (6) explains the operation of abc-dq0 transformation block. If the grid voltage having harmonics, the direct axis (d) follows amplitude of the grid voltage, quadrature axis (q) follows amplitude of the harmonics. In case of third order (3^{rd}) harmonic present in grid voltage then zero-sequence axis (0) follows the amplitude of the zero sequence components.

$$V_d = \frac{2}{3} * [v_a * \sin(\omega t) + v_b * \sin(\omega t - \frac{2\pi}{3}) + v_c * \sin(\omega t + \frac{2\pi}{3})] \qquad (4)$$

$$V_q = \frac{2}{3} * [v_a * \cos(\omega t) + v_b * \cos(\omega t - \frac{2\pi}{3}) + v_c * \cos(\omega t + \frac{2\pi}{3})] \qquad (5)$$

$$V_0 = \frac{2}{3} * [v_a + v_b + v_c] \qquad (6)$$

In second stage, the time invariant signal is averaged by grid frequency. Here harmonics in the time invariant signal is averaged. In third stage, time invariant signal is converted into time varying signal by transforming dq0 signal into abc reference frame. Equation (7) to (9) explains the operation of abc-dq0 transformation block. By this way the fundamental component of grid voltage is extracted and this is also called as reference voltage (Vabc*)

$$V_a = \frac{2}{3} * [v_d * \sin(\omega t) + v_q * \cos(\omega t) + v_0] \qquad (7)$$

$$V_b = \frac{2}{3} * [v_d * \sin(\omega t - \frac{2\pi}{3}) + v_q * \cos(\omega t - \frac{2\pi}{3}) + v_0] \qquad (8)$$

$$V_c = \frac{2}{3} * [v_d * \sin(\omega t + \frac{2\pi}{3}) + v_q * \cos(\omega t + \frac{2\pi}{3}) + v_0] \qquad (9)$$

PLL is used to analyse phase information of the three phase voltage. In proposed scheme PLL can be implemented using MATLAB simulink tool.

C. Reference Current Generation Technique

The reference current algorithm generates reference current for desired power injection. Equation (10) to (12) is used to derive reference current from reference voltage. Reference power is the desired amount power injection to grid.

$$i_a * = \frac{p_{ref} . v_a *}{v_a *^2 + v_b *^2 + v_c *^2} \qquad (10)$$

$$i_b * = \frac{p_{ref} . v_b *}{v_a *^2 + v_b *^2 + v_c *^2} \qquad (11)$$

$$i_c * = \frac{p_{ref} . v_c *}{v_a *^2 + v_b *^2 + v_c *^2} \qquad (12)$$

D. Hysteresis Current Controller

Hysteresis current controller is used to generate PWM pulse according to difference between actual and reference current. In this controller, reference current is subtracted with actual current. The difference in two signals makes error signal which is given to relay network.

The relay network error signal is compared with band limit. Band limit is chosen as 2% of grid current that is 0.2 to -0.2. Here 0.2 is upper band limit and -0.2 is lower band limit. Output of relay is 1 when error is equal to

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upper limit (0.2) and -1 when error is equal to lower limit (-0.2).

Output relay network is compared with zero and produce corresponding PWM signal. Here, output from relay is compared with two conditions. That is, output of relay greater than zero and output of relay less than zero. If output is greater than zero corresponding PWM pulse is given to gate terminal of IGBT1 and output is less than zero is given to gate terminal of IGBT4.

TABLE I
Design details of the system.

Grid line-line voltage	400V
Grid phase voltage	240V
DC link voltage	650V
Grid Frequency	50Hz
Maximum switching frequency	5KHz
Current limit (Δi)	0.4

IV. DESIGN OF MAGNETICS

The most significant part for the voltage drop in the line reactance is due to the variation in consumption of grid current. The reactive component in the line current is eliminated by series compensated network. In grid connected system series inductor is used as static Var (reactive power) compensator. The series inductor draw lagging current and it is also known as absorbers of reactive power. The value of series inductance is calculated using equation (13). In equation (13) DC link voltage (Vdc) is calculated in terms of grid voltage (***e***b) with inductor (L) and current band limit (Δi).

$$V_{dc} = L\frac{\Delta i}{\Delta t} + e_b \qquad (13)$$

$$L = \frac{V_{dc} - e_b}{2 * f_s * \Delta i} \qquad (14)$$

The equation (14) is derived from equation (13) which is used to derive series inductance value (L). The switching frequency (fs) is the frequency to switch from OFF state to ON state which is 5 KHz. Table 1 shows the design details of the system. Substitute the tabulated values in equation (14) we get series inductance value as 62.5mH.

V. SIMULATION AND RESULTS

In this section simulation of grid connected PV array fed inverter is presented. The fig.3 shows the overall simulation diagram of grid connected PV array fed inverter. Fig.4 shows the subsystem of PV array circuit. In proposed scheme, PV array modeling based on equation (15) to (20). Model calculates the short circuit current (Isc), Current through the diode (Id), Open circuit voltage (Voc) and Maximum power (Pm) during variation in Temperature (T) and Irradiance (Q). Series resistance (Rs) values depend on Temperature (T) and Irradiance (Q). Using equation (20) we found (Rs) values for different irradiance and temperature condition. Fig.5 shows the waveform of maximum power transferred from PV array.

From the equivalent circuit, the PV current is given by

$$I_{pv} = I_{sc} - I_d \qquad (15)$$

The current flowing through the diode is given by

$$I_d = 10^{-9} I_{sc} \exp\frac{20.7}{V_{oc}}(V_{pv} + I_{pv}R_s) \qquad (16)$$

Variation in open circuit voltage is given as follows,

$$V_{oc} \cong V_{oc}(1 - \gamma\Delta T)\ln(l + \beta\Delta Q \qquad (17)$$

Variation in short circuit current is given as follows,

$$I_{sc}(Q,T) \cong I_{sc}Q(1 + \alpha\Delta T) \qquad (18)$$

Variation in maximum power is given as follows,

$$P_m(Q,T) \cong P_m \frac{I_{sc}(Q,T)V_{oc}(Q,T)}{V_{oc}I_{sc}} \qquad (19)$$

Updated series resistance is given as

$$R_{se}(Q,T) \cong \frac{P_m(Q,T)}{I_m{}^2(Q,T)} - \frac{V_{oc}(Q,T)}{20.7[I_{sc}(Q,T) - I_m(Q,T)} \qquad (20)$$

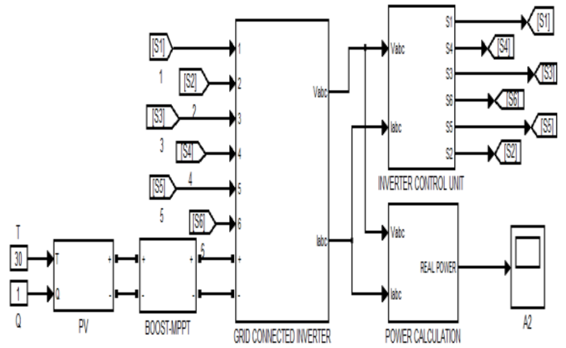

Fig.3. Simulation of grid connected PV array fed inverter.

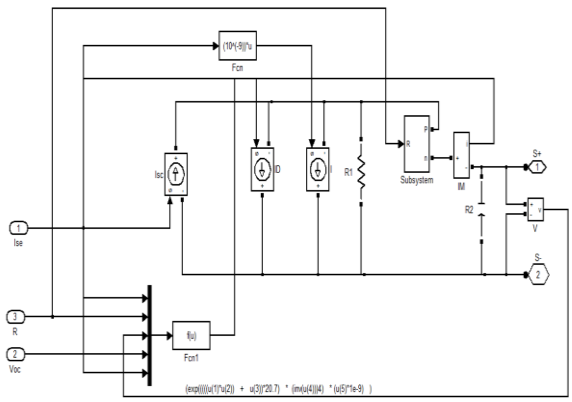
Fig.4. Sub-system for PV array circuit.

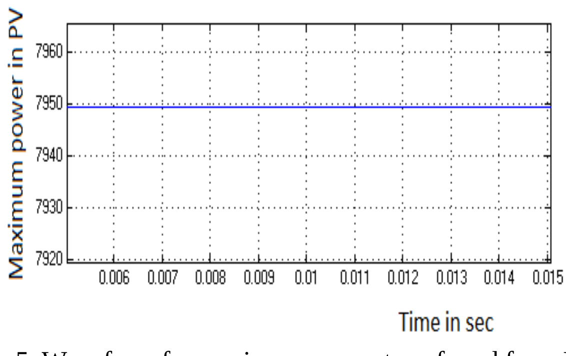

Fig.5. Waveform for maximum power transferred from PV array.

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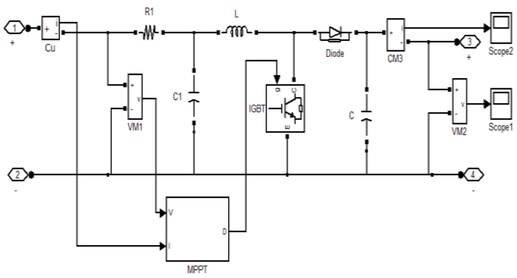

Fig.6. Sub-system for boost converter with MPPT controller.

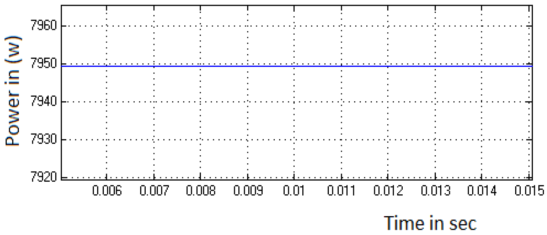

Fig.7. Waveform for maximum power tracked by the MPPT controller

Fig.6 shows subsystem of boost converter with MPPT controller. Here gate terminal of the boost converter IGBT is controlled by MPPT controller. The operation of P&O based MPPT controller is explained in section 3. Fig.7 shows the maximum power tracked in MPPT controller. The output voltage of boost converter (or) DC link voltage is shown in fig.8. The subsystem of grid tied inverter is shown in fig.9. In proposed scheme, grid having 3rd and 5th order harmonics. Fig.10 shows the grid voltage waveform. In fig.11 frequency spectrum of corresponding grid voltage is shown. Here grid voltage having 20% of THD. Fig.12 shows the subsystem of park transformation.

The output voltage of abc-dq0 reference frame is shown in fig.13. Here direct axis follows amplitude of the grid rms voltage. Quadrature axis follows amplitude of the harmonics in the grid voltage. Zero sequence axis follows the amplitude of the 3rd order harmonic in the grid voltage. The output waveform of dq0 to average dq0 is shown in fig.14. The reference voltage waveform is shown in fig.15.Here fundamental component of the grid voltage extracted using PQ theory. The reference current is derived from reference voltage which is shown in fig.16. The actual grid current is shown in fig.17. In grid connected PV array fed inverter scheme, reference and actual grid current should be IN PHASE with them. Fig.18 shows the synchronization of reference and actual current.

The frequency spectrum of the grid current (actual) is shown in fig.19. In proposed method, grid current have been 3.26% THD. The hysteresis current controller compares actual and reference grid current. The corresponding error signal is given to relay network which is explained in section III. The simulation diagram of hysteresis current controller is shown in fig.20. The output of hysteresis current controller is PWM signal which is connected to the inverter's IGBT gate terminal. The power injected to the grid is shown in fig.21. Now power injected to the grid is same as to the maximum power tracked by the MPPT controller.

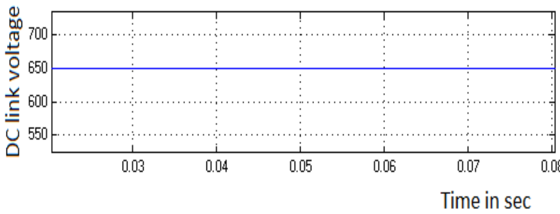

Fig.8. waveform of boost converter output voltage (or) DC link voltage

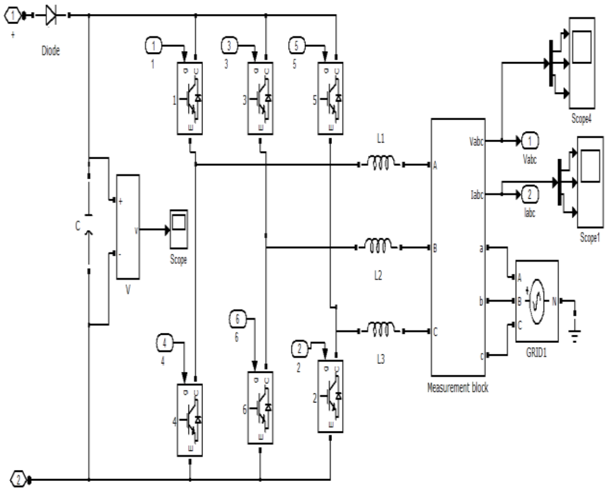

Fig.9. Sub-system for grid tied inverter

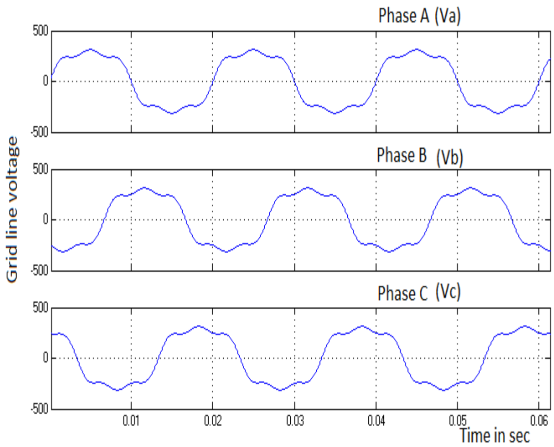

Fig.10. Waveform of Grid voltage.

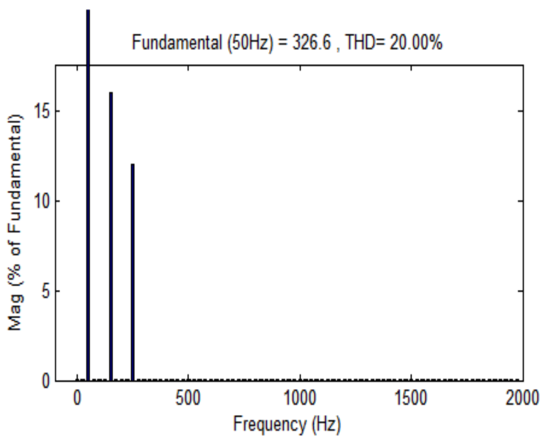

Fig.11. Frequency spectrum of the grid voltage.

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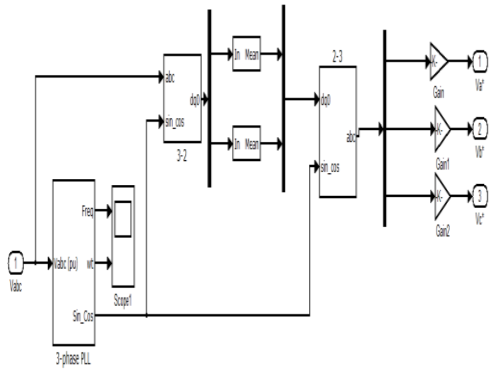

Fig.12. Sub System for PARK transformation.

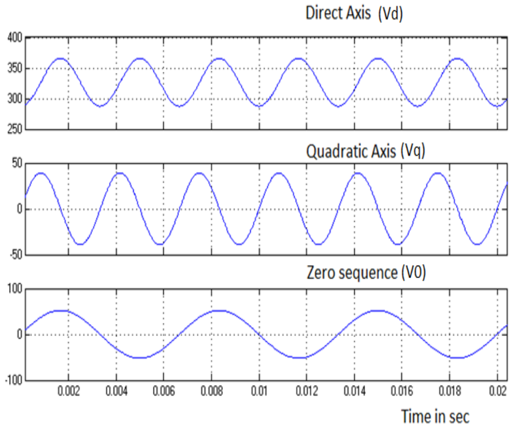

Fig.13. Output waveform of abc-dq0 transformation.

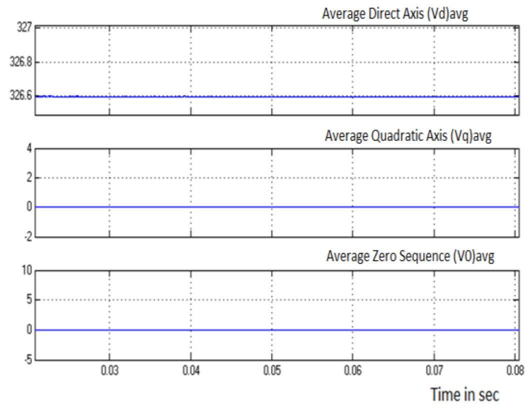

Fig.14. Output waveform of dq0-average dq0 signal.

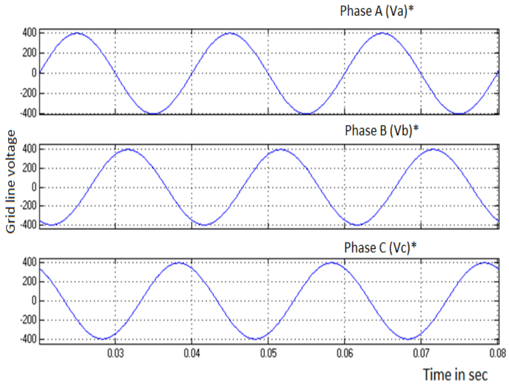

Fig.15. Output waveform of average dq0 to reference voltage.

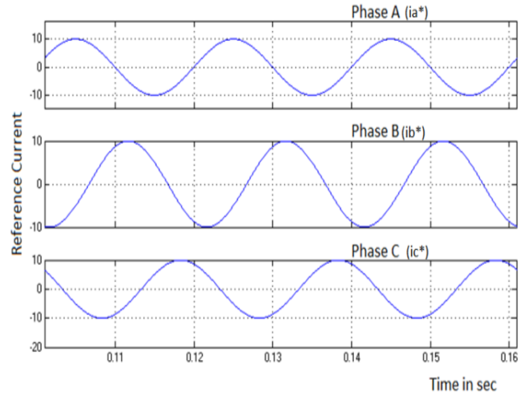

Fig.16. Output waveform of reference current technique.

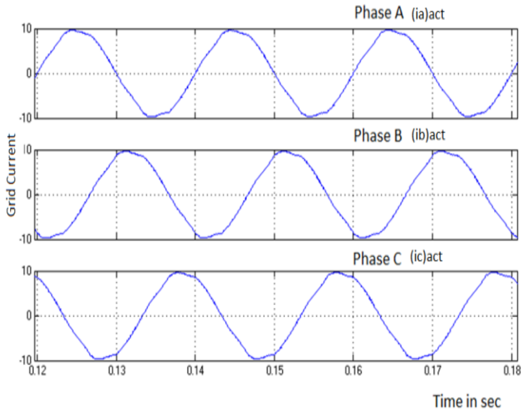

Fig.17. Waveform of actual Grid current.

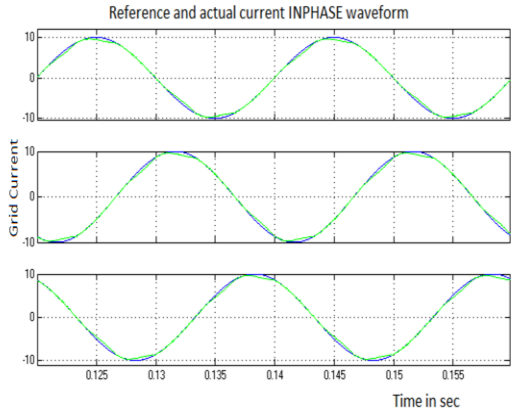

Fig.18. Waveform for reference and actual current synchronization.

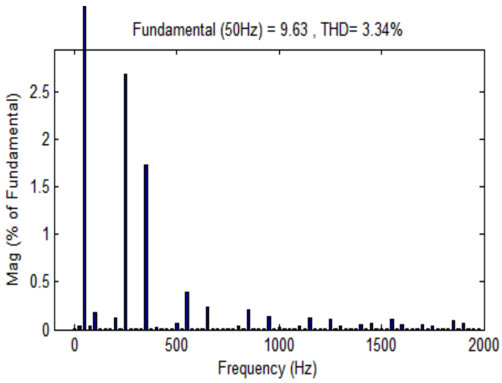

Fig.19. Frequency spectrum of the grid current.

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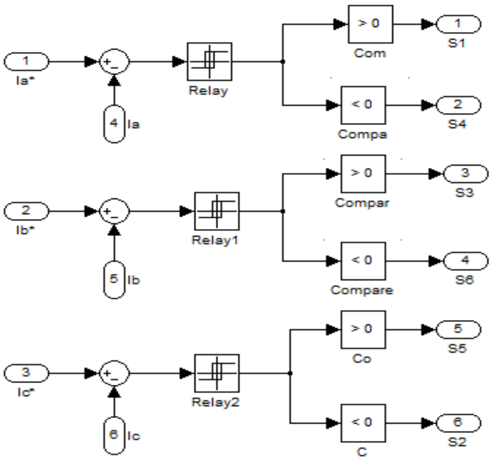

Fig.20. Subsystem of hysteresis current controller.

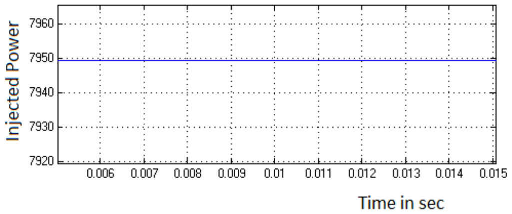

Fig.21. Waveform of real power injected to grid.

VI. CONCLUSION

The design and simulation of a grid interface system for a PV source has been presented. The design of the control scheme is discussed in detail with an illustrative example. It has been shown that the proposed controller is capable of injecting real power to the grid with minimum harmonics in the current, though the grid voltage is distorted with high harmonic content. The simulation results show that the current harmonics is well within the limits despite the voltage harmonics is around 20 %. The design of the magnetics used in the grid interface has also been discussed in detail. The results show that the proposed control scheme is an attractive solution for grid interface of DG sources like PV, fuel cells and wind driven PMSG.

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