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Observer Based Current Controlled Single Phase Grid Connected Inverter

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Abstract

This paper describes a decoupled current control of single phase grid connected inverter achieved through d-q control via observer. The d-q control enables to set zero steady state error. Observer helps in giving a very pure in phase and quadrature components of the fundamental load current, which is being converted into d-q frame through Park transformation and used as the feed-back signal for the control system. In addition to the fundamental component the observer extracts the DC component of the grid current. Injection of these DC component into the grid has been prevented by these controller. This decoupled control has helped in controlling active and reactive components of grid current individually. Therefore by controlling the active and reactive power injected into the grid, the power factor of the grid can be improved. The Simulation study is conducted using MATLAB, considering the grid as a constant voltage source and the results are also incorporated. The performance of the control technique for sudden changes in grid voltage, variation in inductance has been shown through simulation. This control strategy enables in reducing the harmonics in current because of the observer used in feed-back.

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Keywords: Single phase inverter; Decoupled control; Observer; d-q control; DC compensation;

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1. Introduction

Current controlled Single phase inverters are widely used in many grid connected applications such as active power filters, power factor controllers and renewable energy system interface. Recently high penetration of distributed energy systems has increased the demand for single phase grid connected converters [1-3].

Due to high level penetration of distributed energy system, considerable research on current controlled voltage source inverter has been occured. Various control techniques such as PI controller, resonant controller, repetitive controller, deadbeat, predictive controller etc are used to interface with the grid system [4,5]. The controllers gen-

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erally used to control the inverters are stationary frame and synchronous frame controllers. Stationary frame control is otherwise known as sinusoidal tracking. Synchronous reference control is otherwise known as d-q control. For three phase systems d-q control is well known. Simple PI controller can be used to control the synchronous reference frame. It offers infinite gain to dc component at steady state operating point and therefore zero steady state error can be obtained.In d-q control, in-phase and quadrature component of the given sinusoidal signal is required. In three phase system, in-phase and orthogonal component are naturally available. But in case of single phase system it is artificial. In order to control the single phase in d-q reference frame quadrature component is generated artificially. Several methods are used in literature to generate the orthogonal component such as delay the input signal by quarter wave, fictive axis emulation, Hilbert transformation observer etc. [6-9].

This research paper proposes a simple control technique for d-q current control for a single phase inverter using observer and decoupling of the current through decoupled control. In d-q control if the closed loop poles of observer are placed very much closer to origin in s-plane, fundamental components can be estimated with a narrow bandwidth, which will give purer fundamental [10,11]. The transient behavior of the observer will be sluggish and during this transient the system will show coupling. If the closed loop poles of observer are kept far away from origin the performance will be faster and the system will be decoupled.While integrating the any renewable energy based source to the grid, inverter can inject unwanted DC [12,13]. This control scheme also prevents injection of DC into the grid.

This paper is organized as follows. Section 2 describes the proposed control scheme. Section 3 contains transfer function model of the system as well as the tuning of the controller. Section 4 discusses the results to prove the performance of the controller.

2. Observer Based Control Scheme for Grid connected Inverter

The schematic of the proposed control scheme is shown in Fig. 1. The current controlled voltage source inverter is connected to the grid. Here grid current and grid voltage are measured and fed to the control circuit so as to generate the pulse width modulated signal (PWM) for the current controlled inverter. Grid voltage is used for the unit sine cosine generation required for Park transformation as well as Inverse Park transformation. The fundamental in-phase and quadrature component of grid current is estimated, which is transformed to d-q synchronous reference frame and is used as the feed-back signal. Error in d-q currents is fed to respective Proportional Integral (PI) controller. The effect of voltage drop across the inductance is eliminated through non-interactive control. Total control signal in direct axis comprises of the PI output, coupling term and grid voltage.

The observer estimates the DC component along with fundamental in-phase and quadrature component of the grid current. These DC component is made zero and added with the control signal for PWM generation for the inverter.

2.1. Observer

Observability means the estimation of initial state of the state variables based on finite Input-Output observations. Estimation of state variables depends on the real part of the closed loop poles assumed. Pole placement technique is used for calculating the observer feed-back gains (D) $[d_{01}, (d_{11}, d_{12})]$.
System is considered as an oscillator generating a signal of frequency ω rad/s. State space model for this is

$$\dot{X} = AX \tag{1}$$

$$y = C^T X \tag{2}$$

where

$$A = \begin{bmatrix} A_0 & 0 \\ 0 & A_1 \end{bmatrix}, A_0 = 0, A_1 = \begin{bmatrix} 0 & \omega \\ -\omega & 0 \end{bmatrix}, X = \begin{bmatrix} x_{01} \\ x_{11} \\ x_{12} \end{bmatrix} \text{ and } C^T = [1 \;\; 1 \;\; 0]$$

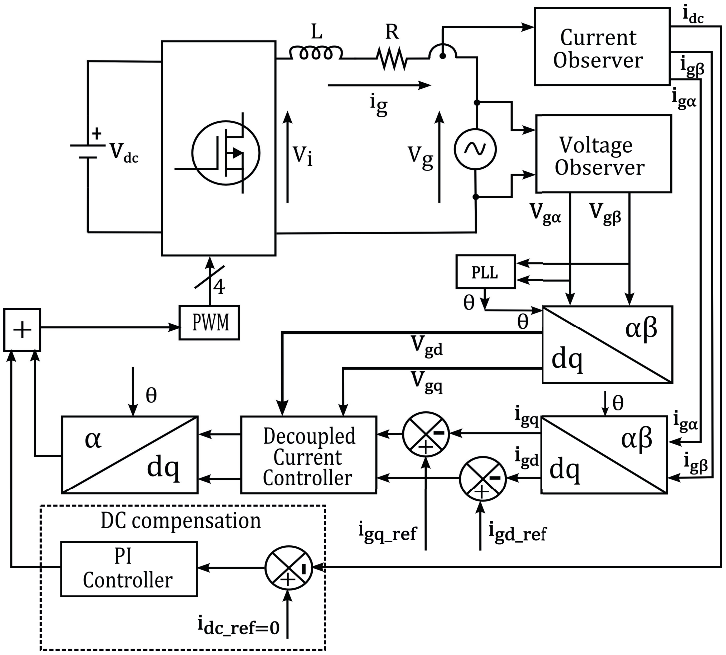

Fig. 1. Schematic of proposed control technique.

The model designed for estimating the state variables, otherwise called as observer represented in state space model as

$$\dot{\hat{X}} = A.\hat{X} + D(y - C^T\hat{X}) \tag{3}$$

where e is the error in output from system as well as model.
Error differential equation is obtained as

$$\dot{E} = (A - DC^T)E \tag{4}$$

where E is the error in actual and estimated state variables. The roots of the error differential equation are the closed loop poles of the observer. Observer feed-back gains $[d_{01}, (d_{11}, d_{12})]$ are designed using pole placement technique. the closed loop poles of the observer assumed to be equidominant at $s = -a\omega$ for DC component and $s = -a\omega \pm j\omega$ for the fundamental components. Transfer function model of the observer d-q model is $1/(1 + sT_{ob})$, where $T_{ob} = 1/(a\omega)$ time constant of observer decides the response time as well as filtering of the signal.

Fig. 2(a) shows the schematic for the single phase observer and Fig. 2(b) demonstrates the in-phase and quadrature component of a 50Hz input sinusoidal signal estimated by the observer within one a half cycle. Here the closed loop poles have real part at s = -100π. DC component in the input signal as well as output signal of the observer is zero.

2.2. Grid connected inverter

The mathematical model of the grid connected current controlled voltage source inverter is given below.

$$V_i = V_g + Ri_g + L\frac{di_g}{dt} \tag{5}$$

where V_i=fundamental voltage of inverter,V_g=Grid voltage and i_g=Grid current
Inverter voltage can be written in alpha-beta reference frame as follows:

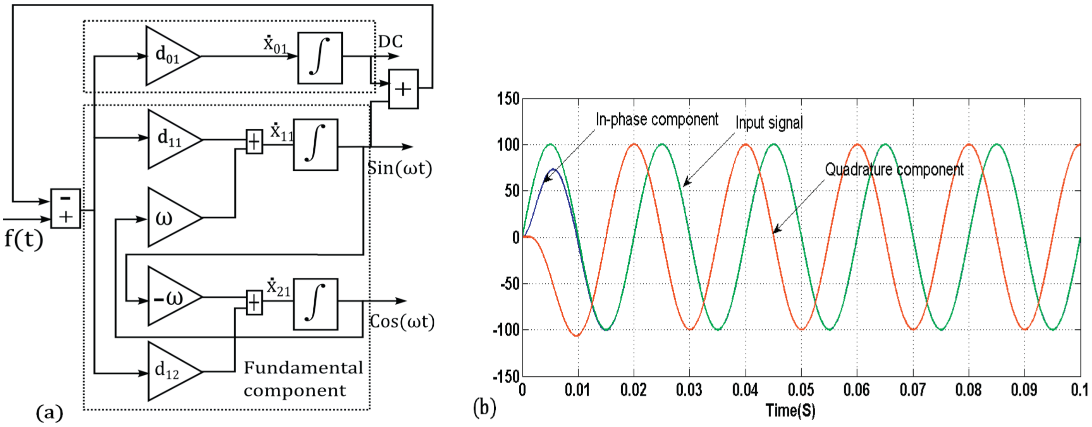

Fig. 2. (a)Schematic of observer (b) Estimated signal froom observer merged with the input signal.

$$\begin{bmatrix}V_{i\alpha}\\V_{i\beta}\end{bmatrix}=\begin{bmatrix}V_{g\alpha}\\V_{g\beta}\end{bmatrix}+R\begin{bmatrix}i_{g\alpha}\\i_{g\beta}\end{bmatrix}+L\frac{d}{dt}\begin{bmatrix}i_{g\alpha}\\i_{g\beta}\end{bmatrix} \tag{6}$$

suffix α and β represents voltage and current in stationary reference frame.
Above equation in stationary frame is transformed into synchronous reference frame using rotation matrix (T) given below

$$T=\begin{bmatrix}cos\theta & sin\theta\\-sin\theta & cos\theta\end{bmatrix} \tag{7}$$

The d-q model of the grid connected inverter is

$$\begin{bmatrix}V_{id}\\V_{iq}\end{bmatrix}=\begin{bmatrix}V_{gd}\\V_{gq}\end{bmatrix}+\begin{bmatrix}R & -L\omega\\L\omega & R\end{bmatrix}\begin{bmatrix}i_{gd}\\i_{gq}\end{bmatrix}+L\frac{d}{dt}\begin{bmatrix}i_{gd}\\i_{gq}\end{bmatrix} \tag{8}$$

Fig 3.represents the schematic of grid connected inverter.

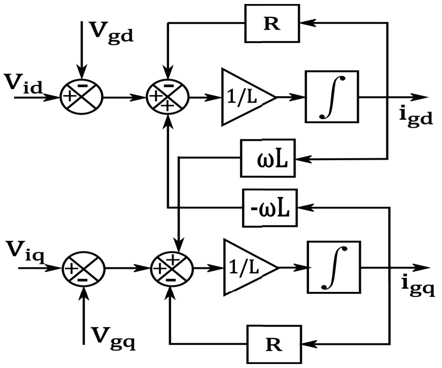

Fig. 3. Inverter model in synchronous $(d-q)$ reference frame.

where d and q represents the direct and quadrature component. The d-q model shows that there is coupling between the direct and quadrature axis because of ωL term. Also the d-q model helps to design simple controller which can give the desired output.

Active (P) and reactive power (Q) calculation in d-q reference frame for single phase system is given by the following formulae:

$$P = (V_{gd}i_{gd} + V_{gq}i_{gq})/2 \tag{9}$$

$$Q = (V_{gq}i_{gd} - V_{gd}i_{gq})/2 \tag{10}$$

In decoupled system, sinusoidal grid voltage is considered as reference, $V_{gq} = 0$ in which therefore active power and reactive power is directly proportional to the i_{gd} and i_{gq} respectively.

$$P = +V_{gd}i_{gd}/2 \tag{11}$$

$$Q = -V_{gd}i_{gq}/2 \tag{12}$$

2.3. Controller

In this proposed scheme PI controller and decoupled control are used. PI controller is used for attaining zero steady state error for the fundamental current components. As the grid connected inverter model has a coupling because of the inductance, the effect of which has been eliminated through decoupled control in d-q frame.

Study of decoupled control is carried out with estimated values of I_{gd} and I_{gq} as input to the decoupled control circuit. When the estimated value of grid current is used for decoupling, expression for inverter voltage is

$$V_{id} = V_{gd} + V_{cd} - i_{gd}\omega L \tag{13}$$

$$V_{iq} = V_{gq} + V_{cq} + i_{gq}\omega L \tag{14}$$

Fig 4 describes the schematic of current controller used for this system. one more PI controller is present in the proposed controller, used for DC compensation, so that injection of DC can be prevented into the grid as shown in Fig (1).

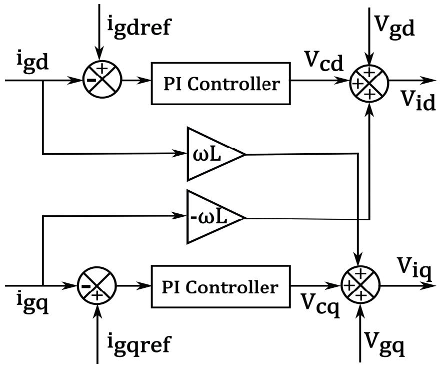

Fig. 4. Current controller in d-q frame.

3. Transfer function model for the proposed system

Fig.5 shows the transfer function model of the decoupled grid connected system. Continuous time models are useful in analyzing the system stability as well as for the turning the PI controller.

In this proposed system, controller designed using the pole cancellation method. Zero of the Controller is chosen such a way that cancels the dominant pole of the closed loop system. Observer pole are placed in faraway from the system pole.

Transfer function of the system with observer is $(20/(1 + 0.24s)(1 + 0.0032s))$ root locus for this is shown in Fig (6.a). This shows for any value of k the system is stable. Integral part is added to this will introduce a pole at origin which makes the closed loop system shows unstable as shown in Fig (6.b). Now addition of zero, cancels this and make the closed loop system more stable as shown in Fig (6.c).

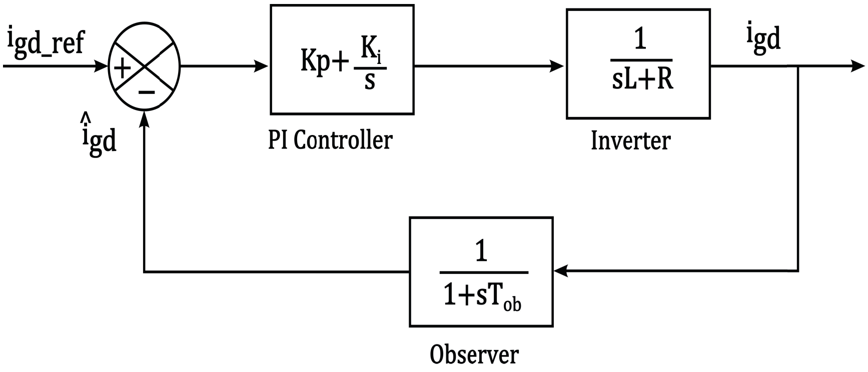

Fig. 5. Transfer function model.

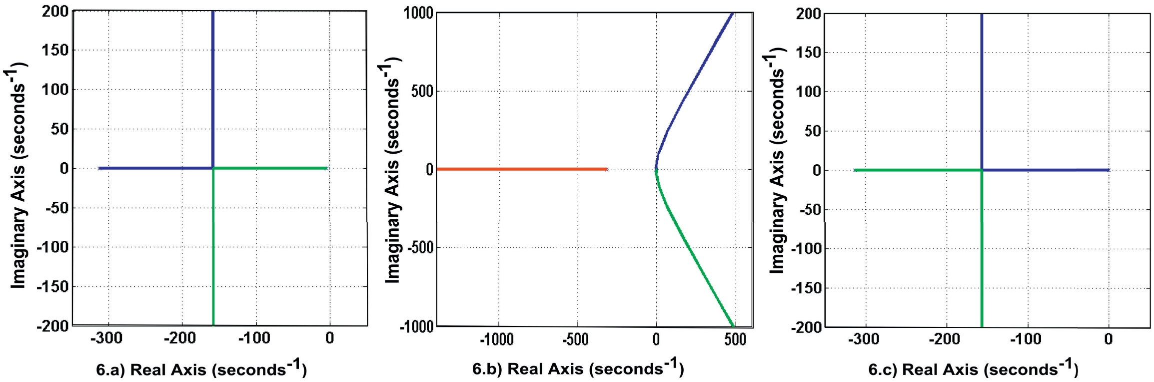

Fig. 6. a) Root locus of the system, b) Root locus of the system with addition of pole at origin and c) Root locus of the system with addition of zero and pole.

4. Simulation Results

Simulation study for a grid connected inverter with the proposed controller is executed using MATLAB Simulink. The specifications for the system are as given in Table I.

Table 1. Parameters used for this simulation

Parameter	Value
Peak grid voltage	100 V
Frequency	50Hz
Switching frequency	10kHz
Inverter inductance	12 mH
Parasitic ristance of the inductance(R)	0.05 Ω
DC-link voltage (V_{dc})	150 V

4.1. Step disturbance in direct and quadrature axis components of grid current

To verify the performance of the controller at 0.5s a step disturbance of 5A is given in the direct axis component of grid current. When steady state is reached again a step disturbance of 10A is given at t=1s. Similarly a step disturbance of 2A is given in quadrature axis component of grid current at t=1.5s. Fig 7 illustrates this. Observer used in the feedback filters the switching noise and gives pure signal. Resulting grid current waveform with the controller in loop for these disturbances mentioned above is shown in Fig 8. Also the grid current attains the steady state within two cycles. The total harmonic distortion (THD) in current is found to be very less as marked in Fig 8. Fig 9 shows the active and reactive component of power injected into the system with respect to there disturbances mentioned above. Fig 10 demonstrates unity power factor at the grid as $i_d = 5A$ and $i_q = 0$ for the controller.

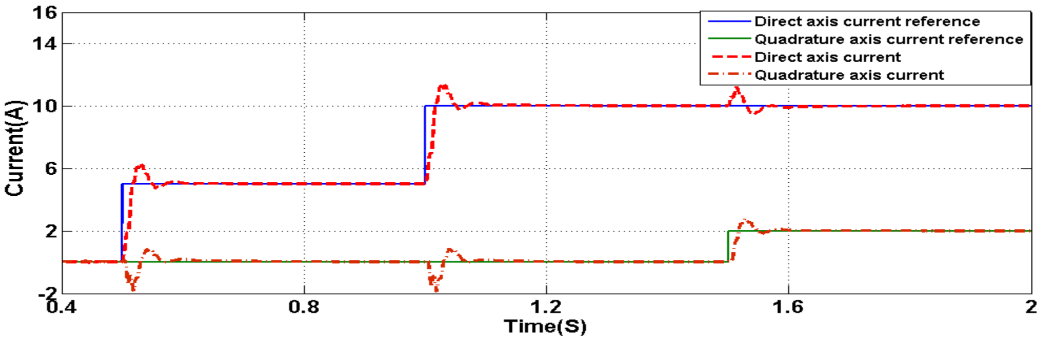

Fig. 7. Direct and Quadrature axis current response of the system corresponding to disturbance given at t=0.5s, 1s and 1.5s.

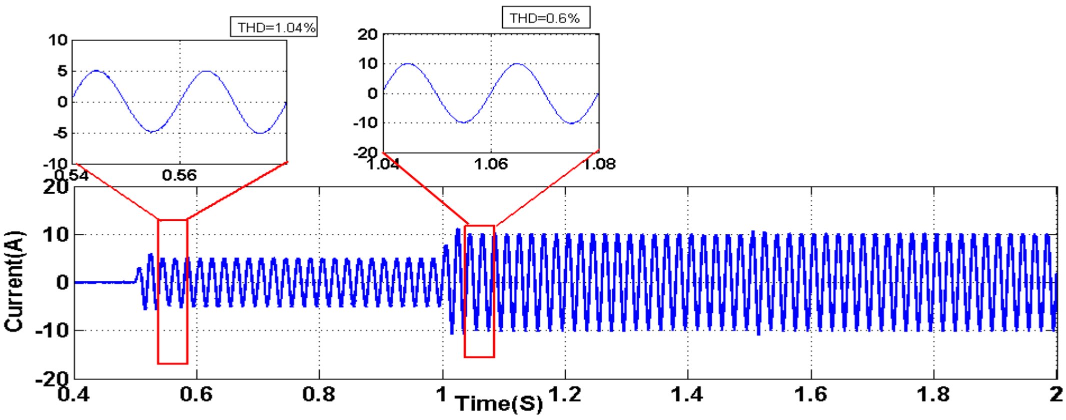

Fig. 8. Respected grid current waveforms for the disturbances in d and q current.

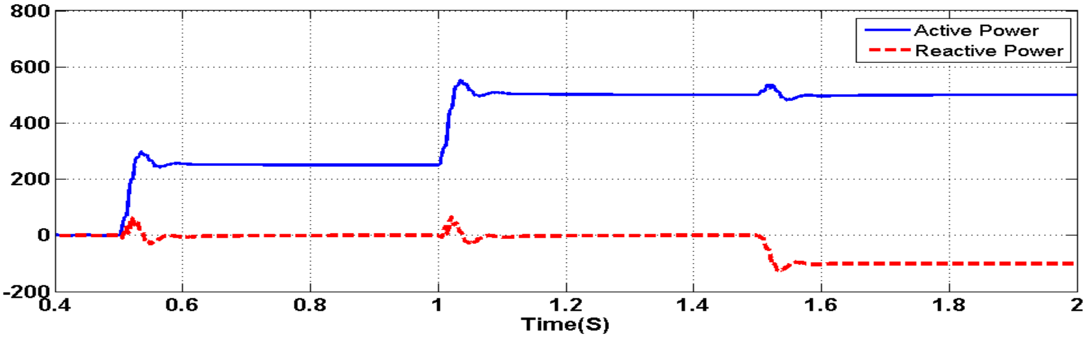

Fig. 9. Active and reactive power injected into the grid with respect to the disturbances considered.

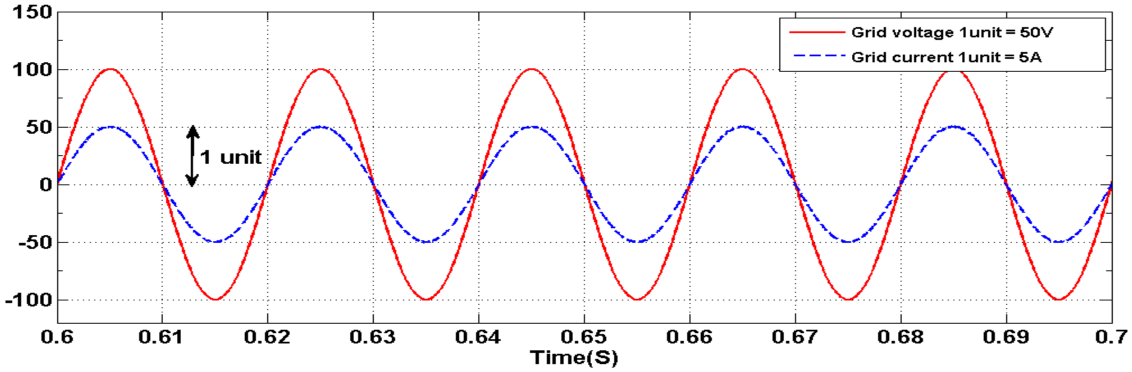

Fig. 10. Grid voltage and grid current under steady state when $i_d = 5A$ and $i_q = 0A$.

4.2. Sensitivity to injection of DC current into the grid

In current controlled grid connected inverter due to non ideal characteristics of the inverter a DC component will be injected into the grid. To study the performance of the controller an additional DC current of 1.5A is injected into the grid from t=0.5s. Fig 11 shows grid current along with this injected DC current. The controller nullifies effect of DC component within few cycles depending upon the level of DC disturbance.

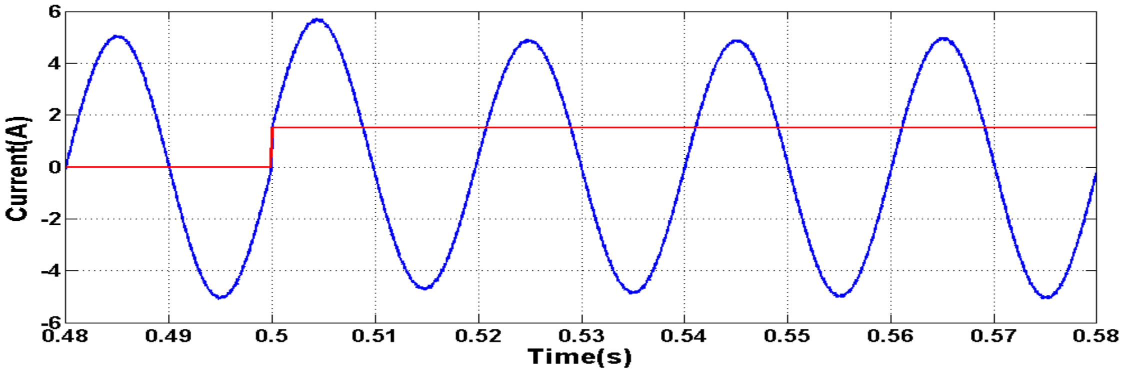

Fig. 11. Performance of the controller for DC current injection into the grid from t=0.5s.

4.3. Sensitivity to variations in inductance

For studying the sensitivity of the controller to variation of inductance, the inverter inductance is changed by ±10% of its actuals.

Fig 12 & 13 shows the direct and quadrature axis grid current for variations in inductance value by ±10% respectively, the system takes about 5 cycles to reach the steady state. As the value of inductance considered is less than the actual, damping is less, whereas the inductance is higher than the actual damping seems to be more.

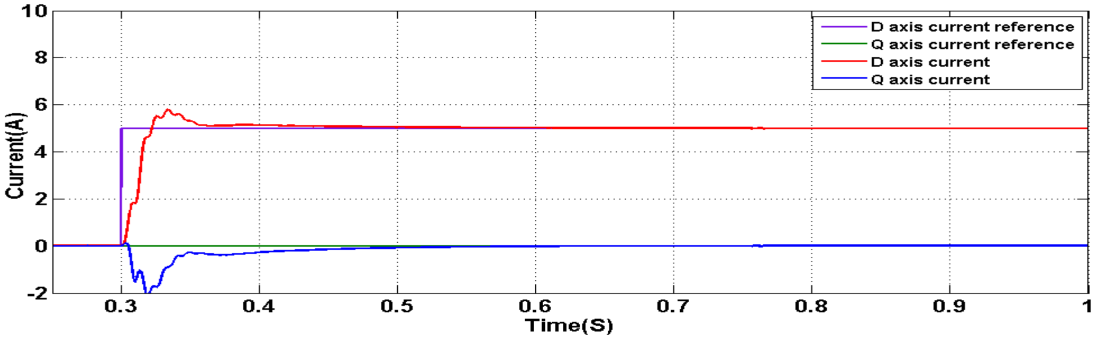

Fig. 12. Performance of the controller for +10% variation in the filter inductance.

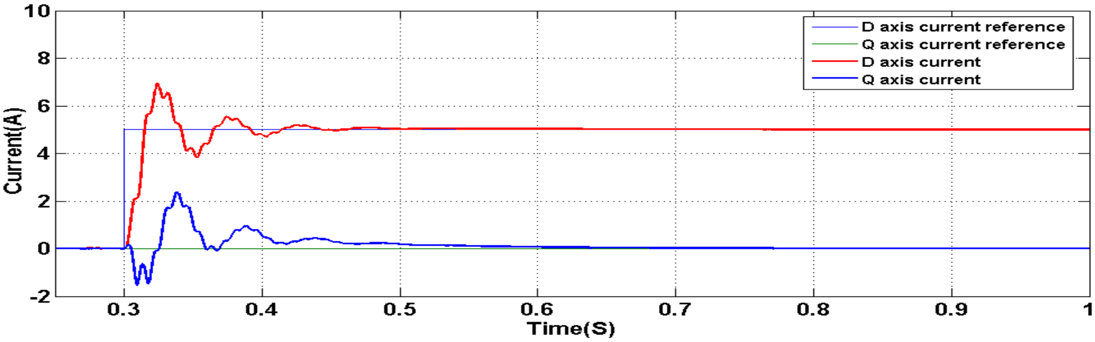

Fig. 13. Performance of the controller for −10% variation in the filter inductance.

4.4. Sensitivity to grid voltage fluctuations

Though the grid is assumed as a constant voltage, normally there is voltage fluctuation in a practical power grid. To study the performance of the controller for grid voltage fluctuations, grid voltage is changed from $95V_{pp}$ to $100V_{pp}$ at t=0.55s and then changed to $105V_{pp}$ at grid at t=0.8s. The direct and quadrature axis grid currents are as shown in Fig 14. The system is able to attain steady state value within 3 cycles.

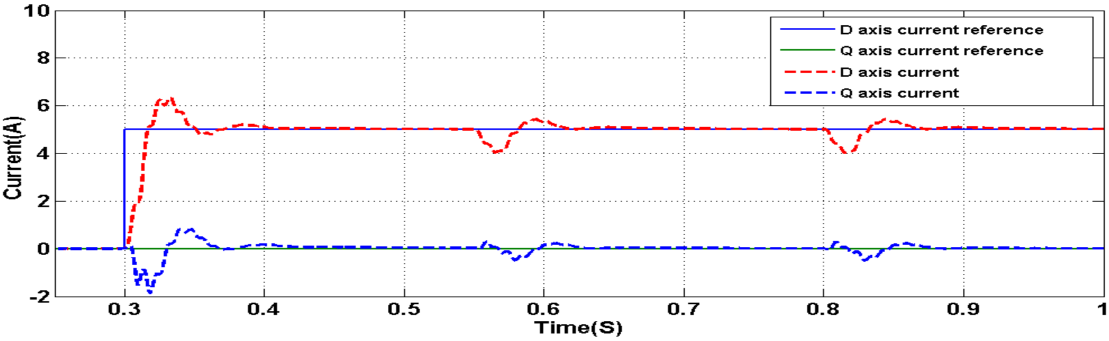

Fig. 14. Performance of the controller for ±5% variation in the grid voltage.

4.5. Comparision of THD in current for different filters

The previous simulation results shown in the paper are with L filter. The grid connected system has been simulated using MATLAB for L, LC and LCL filter while drawing 5A for studying the total harmonic distorion in the current.Inverter side inductance and grid side inductance are 12 mH and 1mH respectively. The value of capacitance filter is choosen is 10μF. The simulation results are tabulated as in Table 2.

Table 2. Comparision of total harmonics distortion(THD) in current

Type	Inverter current THD (%)	Grid current THD (%)
L Filter	1.07%	1.07%
LC Filter	1.07 %	0.93%
LCL Filter	1.07 %	0.05%

5. Conclusion

In this research paper a simple control scheme has been discussed for a single phase grid connected inverter. Observer based control improves the Total Harmonic Distortion in the grid current. This helps in eliminating DC component injected into the grid. Decoupling of current channels in d-q frame provides an independent control of the Active and reactive power. Hence power factor of grid can be improved. Also the d-q current tracking has been shown for ±10% variation in the inverter inductance as well as with fluctuation in grid voltage. This study will help in connecting inverter to a micro-grid, where the fluctuation in voltage and wandering of frequency are more.

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