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Enhancement of Active Power Filter Operational Performance using SRF Theory for Renewable Source

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Abstract

This paper presents the design of Synchronous Reference Frame theory (SRF) based on time domain reference signal elimination technique that can extract reference compensated current for 3ϕ shunt active power filter. A three-phase Voltage Source Converter (VSC) of this system eliminates harmonics current, balances loads and compensates reactive power for power for Power Factor Correction (PFC) or Zero Voltage Regulation (ZVR) at AC main. Fuzzy controller regulates the DC bus voltage at the time of load variation, also provides accurate reference current extraction, frequency independent operation and relatively fast transient response. Hysteresis current controller has current limiting capacity to limit the current error within fixed tolerance band. The grid interfaced solar PV power generating system is tested for PFC and ZVR mode of operation along with harmonics current elimination and load balancing of linear and non-linear loads. Simulation results are presented for the fundamental frequency of 50 Hz.

Keywords: Fuzzy Logic Controller, Hysteresis Current Controller, 4-Leg VSI, SRF Theory

1. Introduction

The Renewable Energy Source is directly connected to the grid. This will inject the harmonics in the power grid and also produce the power quality problems in the power grid. The power quality has degraded due to the increase of the power electronics equipment for developing efficiency interfacing for renewable energy to the grid[1]. The wide usages of the non-linear loads are responsible for harmonic problems and have the significant impact on the quality of the power supply. The main objective of this paper is to design. The shunt active filters with modified control algorithm interface to the grid for compensating the reactive power and harmonic elimination.

In the proposed work it is shown that the grid interfacing inverter can effectively be utilized to perform following important functions:

- Transfer of the active power filter harvested from the renewable resources.
- Load reactive power demand support.
- Current Harmonic Compensation at PCC (Power Capacitor Chip) unbalance and neutral current compensation at increase of 3-phase 4-wire system[1,15]. This Paper presents the mathematical model of the 4L-VSI and the principle of operation of the proposed predictive control scheme, including the design procedure[2]. The total harmonic distortion measures how much of a waveform power is distortion earns by the harmonics to power of fundamental frequency. If the fundamental frequency of the signal f_1 with corresponding power $P_{i,}$ the THD is given in equation (1).

$$THD = \sum_{i>1} \frac{P_i}{P_1} = \frac{P_{Total} - P_i}{P_1} \tag{1}$$

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Where P_{Total} is the total power of the wave form. In other words, the total harmonics distortion is the ratio of the power of all harmonics with the powering the fundamental theory. Squared RMS Voltage is equivalent to power and can replace it in the THD Current equation.

$$THD = \left(\frac{\sqrt{\left(V_2^2 + V_3^2 + V_4^2 + ... + V_n^2\right)}}{V_1} \right) * 100 \qquad (2)$$

2. Block Diagram

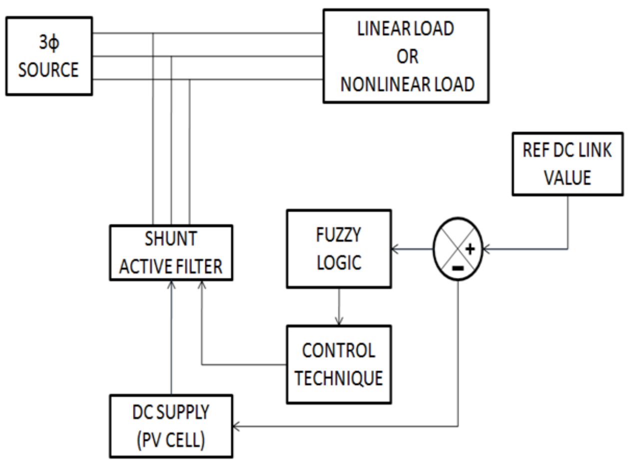


Figure 1. Block Diagram of the proposed system.

The basic block diagram of the proposed system for both linear and non-linear loads is shown in Figure 1. The distortions in the injected current to the grid by the renewable energy source are considerably reduced by the effect of shunt active filter[12,13]. The inverter used in renewable is controlled by the fuzzy logic controller and the hysteresis current controller. The open loop circuit diagram of the proposed system is shown in Figure 2.

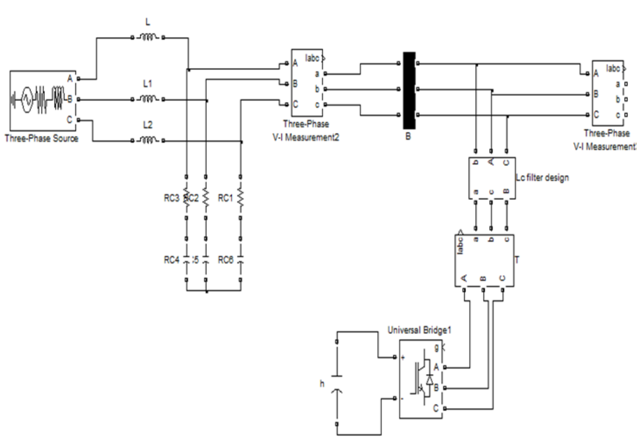


Figure 2. Proposed Simulated Diagram in open loop.

3. Control Strategy

3.1 Hysteresis Current Controller

The actual Current signal is compared with the given current signal of the inverter by hysteresis current control. If the current signal of any phase exceeds the reference current signal a certain range, we can change the switching state of the inverter to control the change of the actual current signal in order to track the given current signal[1,7].

Hysteresis current control has a series of advantages such as relatively faster response, internal current limiting capability and stability. Based on the above advantages, hysteresis current controller is widely used in applications like power inverters, AC drives and so on[2,8].

For a three phase PWM conventional hysteresis controller three phases are implemented independently for each phase and the switching signal are generated independently. In the conventional hysteresis controller for the case of positive current input, if the error between the phase current (i_{ph}) and the reference sinusoidal current (i_{ref}) exceeds the upper hysteresis limit h+, the switch of the corresponding phase is turned off thus causing phase current to decrease. Once when the phase current reaches its lower hysteresis limit h-, the switch is turned on again so that the phase current increases. The high difference in the rate of change between the generated current and the reference current at any point leads to unsymmetrical ripple at that point.

There are various Pulse width modulation techniques. The hysteresis band current controller is one among them and very often used because of its simplicity of implementation and to reduce the switching losses for variable frequency and to make the generated current swing symmetrically with minimum ripple. Also, besides fast response current loop, the modulation method does not need any knowledge of load parameters but depends only on tuning of hysteresis band for periodical sampling system. However, the current control with a fixed hysteresis band has the disadvantage that the PWM frequency varies within a band because peak-to-peak current ripple is required to be controlled at all points of the fundamental frequency wave by tuning the hysteresis band tolerance limit. The method of adaptive hysteresis-band current control PWM technique where the band can be programmed as a function of load to optimize the PWM performance is described in[3]. The basic implementation of conventional hysteresis current control method is based on deriving the switching signals from the comparison of the current error with a fixed tolerance band. Hysteresis control is based on the comparison of the actual phase current with the tolerance band around the reference current associated with that phase. On the other hand, this type of band control is negatively affected by the phase current interactions which is typical in three-phase systems. This occurs due to the interference of the phases, since each phase current of the three phases not only depends on the corresponding phase voltage but is also affected by the voltage of the other two phases. Depending on load conditions switching frequency may vary during the fundamental period, resulting in inverter operation. In [4] the authors proposed a new method that minimizes the effect of interference between phases while maintaining the advantages of the hysteresis methods by using Phase-Locked Loop (PLL) technique to constrain the inverter switching at a fixed predetermined frequency. In this paper, the current control of PWM-VSI has been implemented in the stationary (α, β) reference frame. One method is based on space vector control using multilevel hysteresis comparators where the hysteresis band appears as a hysteresis square. The second method is based on predictive current control where the three hysteresis bands form a hysteresis hexagon. Three hysteresis bands of the width δ are defined around each reference value of the phase currents ia, ib, ic (Figure 3).

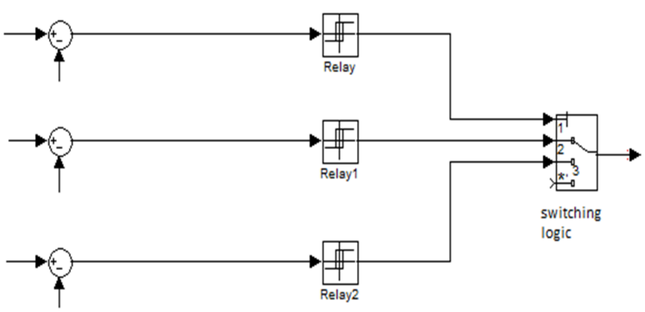


Figure 3. Hysteresis Current Controller.

Hysteresis bands limits are created or tuned around the reference phase currents ia, ib, ic. The goal is to keep the actual value of the currents within their hysteresis bands all the time. As the three currents are not independent from each other, the system is transformed into (d, q) coordinate system. With the transformation of the three hysteresis bands into this coordinate system, they result in a hysteresis hexagon area[9,10]. The reference current vector i_{ref} points towards the centre of the hysteresis that can be seen in Figure 4.

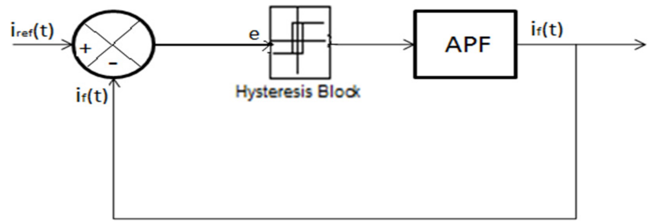


Figure 4. Filter with Hysteresis Control.

The actual value of the current i have to be kept within the hexagon area. Each time when the tip of the current i touches the border of the surface heading out of the hexagon, the inverter switch has to be switched on in order to force the current into the hexagon area. The current error is defined as:

$$i_e = i - i_{ref} \tag{3}$$

The error current generated can be controlled by a two level hysteresis comparator in order to avoid unsymmetrical ripple. A switching logic is necessary because of the coupling of three phases as shown in Figure 2.

When the current error vector i_e touches the edge of the hysteresis hexagon[14], the switching logic has to choose next, the most optimal switching state with respect to the following considerations:

- The current difference i_e should be moved back towards the middle of the hysteresis hexagon as slowly as possible to achieve a low switching frequency.
- If the tip of the current error i_e is outside of the hexagon, it should be returned in hexagon as fast as possible which is important for dynamic response. In order to explain the control method the mathematical equations should be introduced (Figure 3).

According to equation 2, the deviation in current error Is given by:

$$\frac{di_e}{dt} = \frac{di}{dt} - \frac{di_{ref}}{dt} \tag{4}$$

From equations (3) and (4) we have:

$$\frac{di_e}{dt} = \frac{1}{L}\left(v_k - v_{ref}\right) \tag{5}$$

Where the reference voltage v_{ref} is defined by equation (6)

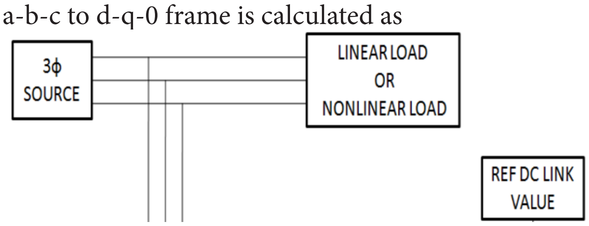
$$v_{ref} = e + L\frac{di_{ref}}{dt} \tag{6}$$

The reference voltage V_{ref} is the voltage which would allow that the actual current i is identical with its reference value iref. In[5] the authors explained why the reference voltage for the current control is the sum of the inner voltage and the voltage across the inductance of the load. The switching logic for the switches has to select the most optimal out of eight switching states according to the mentioned criteria.

3.2 Synchronous Reference Frame Theory

The synchronous reference frame theory or *d-q* theory is based on time domain reference signal elimination technique. If performs the operation in steady state or transient state as well as for generic voltage and current waveforms.

If allows controlling the active power filters in real time system. Another important characteristics of this theory is the simplicity of the calculations, the synchronous reference frame *d-q-0* is determined by transformation angle with respect to the $\alpha - \beta -$ frame applied in the *d-q* theory. It is based on the transformation of the stationary reference frame three phrase variables (a,b,c) to synchronous reference frame variables (d,q,0) whose direct (d) and quadrature (q) axes rotate in space at the synchronous speed W_s, which is the angular electrical speed of the rotating magnetic field of the three phase supply given by the $W_s = 2\pi f_s$, where f_s is fundamental frequency of the supply. ϴ is the transformation from a-b-c to d-q-0 frame is calculated as



(7)

Where, $\theta(t) = \int w_s(t)dt + \theta$ (8)

As Low Pass Filter (LPF) extracts the dc component of the phase current, i_d to generate the harmonic reference component. The LPF is second order for eliminating the higher order harmonics the PI controller is used to eliminate the steady state error of the DC Component of the d-axis reference signals. The DC side capacitor voltage is used for calculating the error voltage. This error voltage is passed through a fuzzy logic controller whose propagation gain (K_p) and integral gain (K_1) is taken as 0.1 and 1 respectively.

VSI require a balanced sinusoidal output voltage for supplying unbalanced and non-linear loads. This requirement is satisfied with the help of the pole placement control technique via state feedback in this work. This Proposed method is found to be effective in achieving an accurate adjustment of the transient performance of the 3 leg universal bridge VSI in tracking its reference input under steady state conditions. A settling time of 0.56ms is achieved. The structure of the shunt active filter is shown in Figure 5.

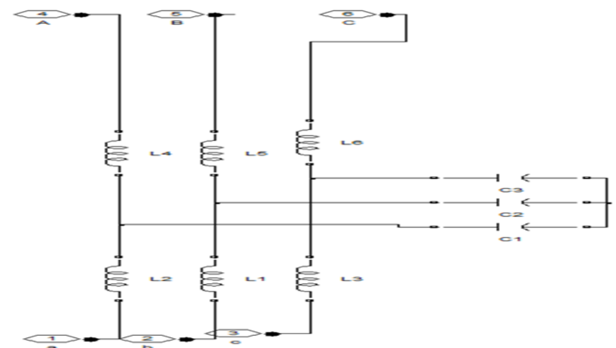


Figure 5. Shunt Active Filter.

4. Simulation and its Result

4.1 Simulation Circuit

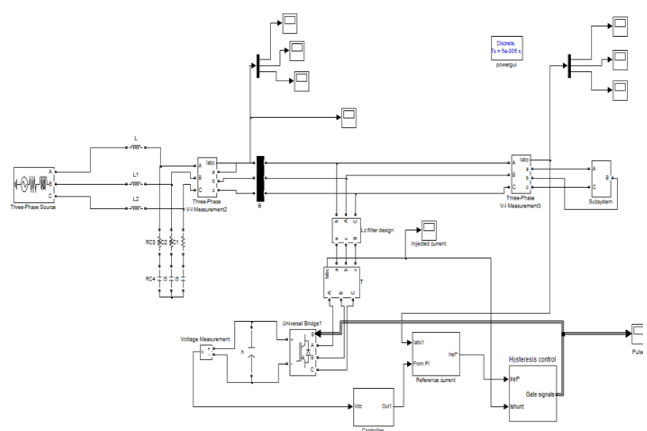


Figure 6. Closed loop simulation circuit diagram.

A three-phase source of 2500 kV, 50 Hz is supplied and given to the grid, using RL filter of 5 mH, 8 ohms. The supplied voltage and current is measured using a three-phase V-I measurement. A capacitance of 4000 mF is obtained by a renewable energy of photovoltaic cell, which is added to the capacitance. The voltage between the capacitance is measured using a voltmeter. The input voltage is given to a fuzzy logic controller, which is compared with the reference voltage of 4700 V; the obtained fuzzy logic output is given to the reference frame or d-q theory. The actual three-phase current of i_a, i_b, i_c is transform using a phase sequence, which is passed through a 2[nd] order low pass filter and compared with the fuzzy logic output signal. Then the d-q-0 is again transformed to a three-phase reference current. The 6-gate pulse is added to the inverter which is obtained when comparing shunt current with reference current in hysteresis comparator. The three-phase current in the inverter is measured using an ammeter, the three-phase current i_a, i_b, i_c is filtered using a LC filtering circuit. Inductance of 10mH and capacitance of 10 micro F is used in the LC filtering circuit. The filtered three-phase current having minimum harmonic distortion is then added to the supply or to the distribution unit.

4.2 Hysteresis B and Controller

The three-phase shunt current is compared with the three-phase reference current using a comparator and the compared output current error is passed through delay time for rectifying the input signal in a relay, which is again passed through delay time to get the gate pulse. Each gate pulse is converted as 0 and 1. Thus the six-gate pulse is obtained.

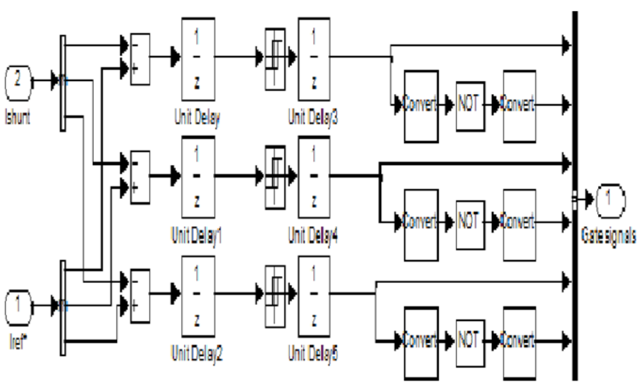


Figure 7. Hysteresis band controller.

4.3 Load

In a load a three phases Asynchronous machine with rotor speed of 240 rpm and electromagnetic torque of 6000kNm is connected.

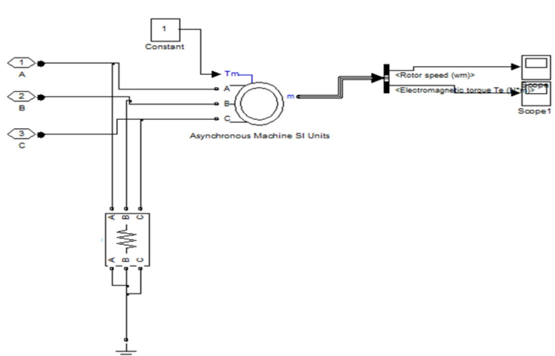


Figure 8. Asynchronous machine has load.

4.4 Reference Current Generation

The three-phase actual current I_{abc} is d-mux to transform to a d-q-0 using a phase sequence[11]; the direct axis is passed through a 2nd order low pass filter, which is compared with the fuzzy output and the real current. And the quadrature axis is compared with the filter output and the real current is shown in Figure 9. The obtained d-q current is passed through a gain multiplier which is d-mux. Thus the obtain d-q-0 is transform to a three-phase reference current using a phase sequence.

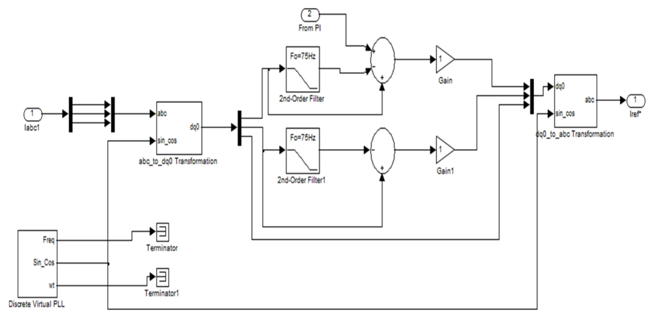


Figure 9. Reference current generation using synchronous reference theory.

4.5 Fuzzy Logic Controller

Figure 10 shows two inputs the Error (e), its Variation (Δe) and one output. Among the various available powers filter controllers PI, PID hysteresis and fuzzy logic controller.

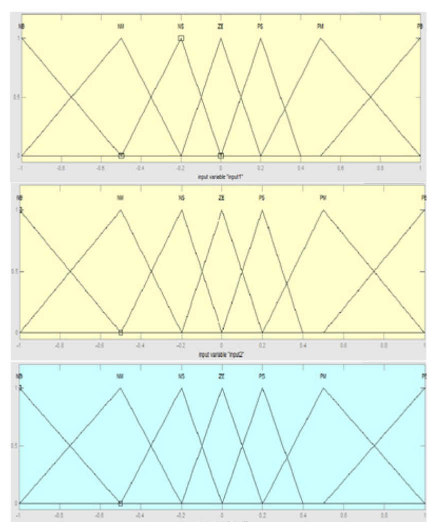


Figure 10. Fuzzy Membership Functions.

In this application, the fuzzy control algorithm is implemented to optimize the energy storage of the DC capacitor voltage based on DC voltage error e(t) processing and its variation Δe(t) in order to improve the dynamic performance of APF and reduce the total harmonic source current distortion. Fuzzy logic uses linguistic variables instead of numerical variables.

In control system, error signal E, its variation ΔE and output signal can be assigned as Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (E), Positive Small (PS), Positive Medium (PM) and Positive Large (PL). The triangular membership function is used for fuzzification process. The process of fuzzification convert numerical variable to a linguistic variable or fuzzy number between 0 and 1.

Fuzzy logic based controller will use fuzzy membership functions (input and output) and inference rules to determine the appropriate process input. Figure 10 and 11 shows the membership function and the fuzzy rules respectively.

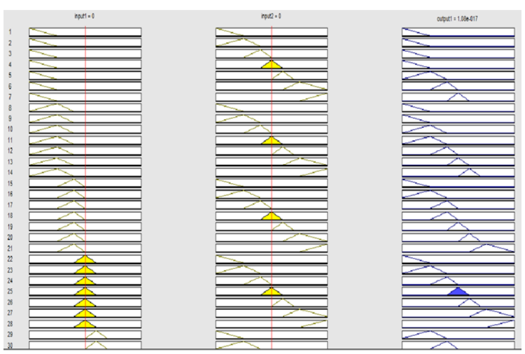


Figure 11. Fuzzy Rules.

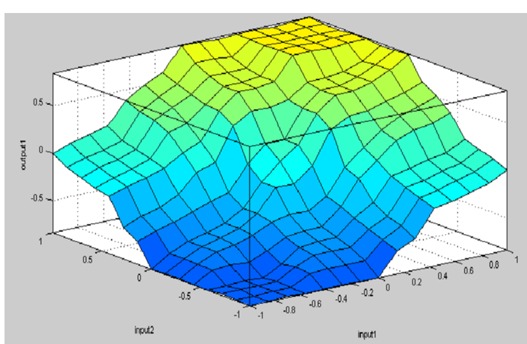


Figure 12. Surface viewer.

4.6 Simulation Results

A simulated model for the three-phase universal bridge PWM inverter was obtained using MATLAB-Simulink. In this paper the current is compensated to get a reduced THD value by use of fuzzy logic controller. The input source current I_a = 250kA, I_b= 230kA, I_c = 260kA. The output supply current I_a=250kA, I_b=230 kAI_c=240kA. The THD (Total Harmonic Distortion) = 0.77%, fundamental frequency is 50 Hz.

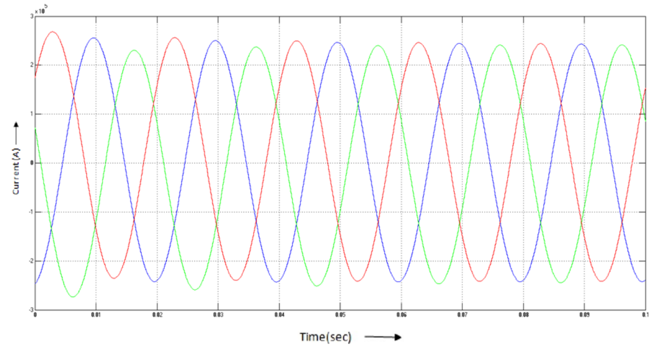


Figure 13. Input three phase current.

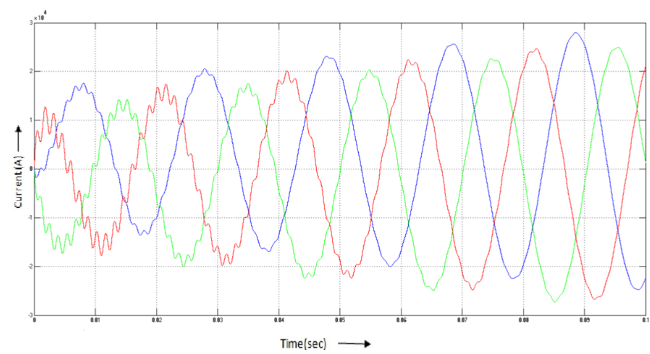


Figure 14. Injected current waveform.

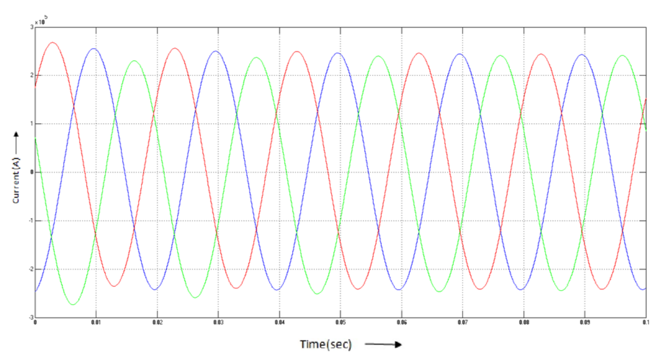


Figure 15. Filtered output current.

5. Conclusion

In the present work hysteresis current controller is used to eliminate the current harmonics thus improving the quality of current to the distribution system from solar PV generating system. A three phase current controlled

Voltage Source Inverter (VSI) with a DC link capacitor across it is used as an active filter. The synchronous reference frame theory (d-q Theory) is used for extracting accurate compensated reference current and Fuzzy Logic Controller (FLC) is used in the reduction of load current harmonics and relatively fast transient response. Hysteresis Band Current Control (HBCC) technique is used for the generation of firing pulses to the inverter. The simulation is carried with asynchronous three phase squirrel cage motor as load and the results are compared with theoretical evaluation.

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