Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 9 Issue 09, September-2020

Control Techniques for Shunt Active Power Filters

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Abstract— **Reliability and quality are two most important facets of power delivery system. Wide use of nonlinear and electronically switched devices in distribution systems hinders the quality of supply. The problems of power quality include voltage fluctuations, flicker, harmonics, and asymmetries of voltages. Specific analysis of power quality issues and their solutions have generated tremendous amount of interest amongst power system engineers. Some of the tuned passive filters were developed to bypass specific harmonic frequencies. Since the passive filters were found to operate only over a fixed range, the attention is to be given towards compensating devices like active filtering that can effectively eliminate the harmonic currents.**

In this paper, the instantaneous p-q technique, synchronous reference frame theory and the hysteresis current control of shunt active filters is studied.

Keywords: p-q technique, Synchronous Reference Frame (SRF) theory, Hysteresis current control (HCC), Shunt Active Power Filters (SAPF)

I. INTRODUCTION

In last few decades due to developments in power conversion technologies the application of non-linear loads has significantly increased in the power system. Switched mode power supplies (SMPS), variable frequency drives, Rectifiers, Converters, Arc Furnaces are some of the non-linear loads found in Industries. Also advances in the technology for development of Renewable energy sources has led to application of various power electronic converters used for increasing its efficiency. Excessive use of these power electronic devices has resulted in distorting the voltage and current waveforms and responsible for reactive power disturbances in the power system such as low power factor, low efficiency, voltage fluctuations and communication interference [2,3,4,6 10,9]. Distorted or non-sinusoidal currents contain other than the desired fundamental frequency component many undesired frequency components which are multiples of the fundamental component.[6]. These frequencies commonly known as harmonics. These harmonics cause distortions in the supply currents and voltages. This causes poor power factor, lower efficiency and interference with communication lines. So it is necessary that these harmonics are reduced. The minimization of harmonics can be done through a combination of active and passive filters [7]. Harmonics is known to be a major issue out of all power quality problems. The increased use of power electronics equipment has resulted in rise of harmonics in the power system. Nonlinear loads connected with the distribution system result in harmonic currents. These current harmonics will be responsible for power factor reduction, power system voltage fluctuations, decrease in efficiency and interference during communications[8]. When the main objective is to eliminate harmonic currents, the shunt active power filter SAPF has been proved to be the best choice [3].
Active power filters (APFs) are a solution to overcome the disadvantage of passive ones. APFs can adapt itself to any load change [5]. The shunt active filter have been researched and developed that they have gradually been recognized as a feasible solution to the problems created by nonlinear loads. They are used to eliminate the unwanted harmonics and compensate the fundamental reactive component consumed by the nonlinear loads through injecting the compensation currents into the AC lines [2]

II. CLASSIFICATION OF ACTIVE POWER FILTERS

The active filters can be classified into various categories. It can be based on converter type, topology and number of phases. Based on the power circuit configuration, they can be classified into shunt, series and hybrid

A. *Series Active Filter:* The Series active filter is the filter that is connected in series with the utility through a matching transformer, so it is controlled to eliminate problems related to voltage, such as voltage harmonics, voltage flicker, voltage balancing and voltage sag. [1,4,9]

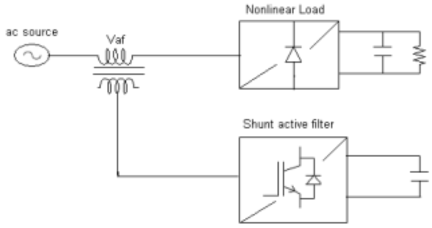

Fig 1: Series Active Power Filter [9]

B. *Shunt Active Filter:* This class of filter configurations is the most important and most widely used type in active filtering. The shunt active filter is the filter that draws a compensating current from a power line to cancel harmonic currents on the source side, a grid location where power quality becomes important. It is widely used to eliminate current harmonics, compensate reactive power and balance unbalanced currents by injecting (drawing) additional current[4,9].

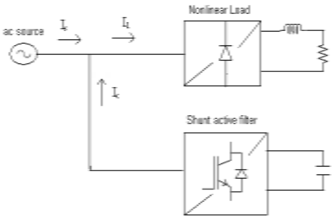

Fig 2: Shunt Active Power Filter[1]

C. *Hybrid active filter*: Hybrid Power Filters (HPFs) are basically the amalgam of Active and Passive filters which helps in considerable reduction in the rating and expenditure on filters. These filters are able to damp out harmonic resonances rather than compensating for only harmonic currents [11].

They can also be classified based on the converter type. It can either be current source (CSI) or voltage source inverter (VSI).
Based on reference signal techniques, active power filters can be classified into frequency domain and time domain.

The principle of operation of an active power filter is to generate compensating currents into the power system for cancelling the current harmonics contained in the nonlinear load current. This will thus result in sinusoidal line currents and unity power factor in the input power system[9]

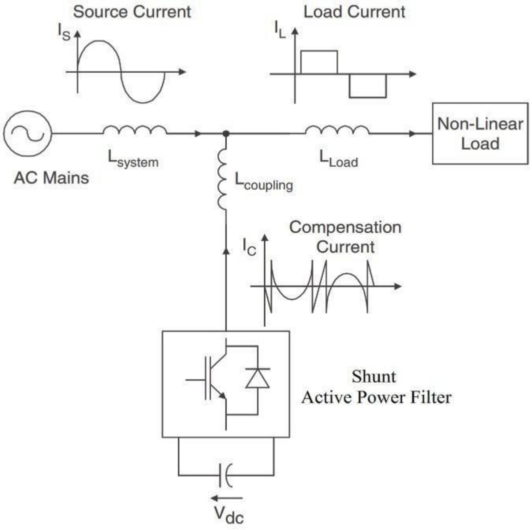

Fig 3: Structure of Shunt Active Filter

It consists generally of two basic blocks; the PWM converter which is responsible for power processing in synthesizing the compensating current that should be drawn from the system and the active filter controller which is responsible for signal processing in determining in real time the instantaneous compensating current references, which are passed continuously to the PWM converter[1].

For compensating load side current harmonics, filter injects harmonic current which is equal in magnitude but opposite in phase. A voltage source inverter (VSI) acts as a SAPF. VSI is controlled such that it inject or absorb a compensating current Ic to or from the system, so as to cancel the current harmonics present on the AC side. The VSI with series connected inductor suppresses the ripple current[4].

$$I_{Source} = I_{Filter} + I_{Load}$$

III. CONTROL TECHNIQUES

A. *Instantaneous Real and Reactive Power Theory*

In 1983, Akagi et al. have proposed the "The Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits", also known as instantaneous power theory , or p-q theory[1]. The p-q theory consists of an algebraic transformation (Clarke transformation) of the three-phase voltages and currents in the a-b-c coordinates to the α-β-0 coordinates, followed by the calculation of the p-q theory instantaneous power components[6]-[8]. It is based on the instantaneous values of the current and voltage of the power system. It is valid for Steady state as well as transient condition[2,3]. The Clark transformation of voltage is given as:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \ldots\ldots(1)$$

also, three phase instantaneous line currents ia, ib, ic can be transformed on αβ0 axes as:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \ldots\ldots(2)$$

and the instantaneous real power is defined as follows

$$p = v_a i_a + v_b i_b + v_c i_c \ldots\ldots(3)$$

From these equations, the instantaneous power can be rewritten as

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \ldots\ldots(4)$$

As the compensator will only compensate the instantaneous reactive power, the real power is always set to zero. The instantaneous reactive power is set into opposite vectors in order to cancel the reactive component in the line current. From the equation 2 & 3, yields equation 5.

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p \\ q \end{bmatrix} \ldots\ldots(5)$$

The compensating current of each phase can be derived by using the inverse orthogonal transformations as shown below in equation 6.

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} \ldots\ldots(6)$$

This method provides better harmonics compensations as the response of the harmonics detection phase is in small delay. The current control strategy plays an important role in fast response current controlled inverters such as the active power filters.

B. Synchronous Reference Frame Theory

The synchronous reference frame theory is used to extract the fundamental positive sequence component of the load current by transformation of iLa, iLb, iLc into d-q reference frame. Reference Frame transformation is the transformation of coordinates from a three-phase a-b-c stationary coordinate system to the 0-d-q rotating co-ordinate system[4,11]. This transformation is important because it is in 0-d–q reference frame where the signal can effectively be controlled to get the desired reference signal[8]. To implement the SRF method, a kind of synchronizing system called as phase-Locked loop (PLL) is used.

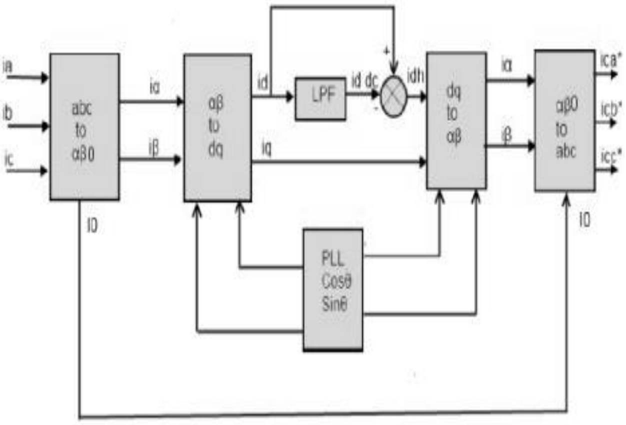

Fig 4: Block Diagram of SRF Algorithm

In this method, the source currents (ia, ib, ic) are first detected and transformed into two-phase stationary frame (α-β-*0)* given in Eq.(1). Now, the two phase current quantities *iα* and iβ of stationary α-β-axes are transformed into two-phase synchronous reference frame d-q-axes using Eq.(2), where cos θ and sin θ represents the synchronous unit vectors which are generated using phase-locked loop system (PLL).

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \frac{\sqrt{2}}{3}\begin{bmatrix} 1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

This harmonic component can be easily extracted from id and iq using a high pass filter as implemented in Fig. 4. The d-axis current is a combination of active fundamental current (id_{dc}) and the load harmonic current (i_h). Thus, AC component i_{dh} can be obtained by subtracting i_{ddc} part from the total d-axis current (id), which leaves behind the harmonic component present in the load current. Inverse transformation is performed to trans form the currents from two - phase synchronous frame d-q into two-phase stationary frame α-β as per Eq.(3).

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} i_{dh} \\ i_q \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Thus, the current from two phase stationary frame α-β-0 is transformed back into three-phase stationary frame a-b-c as per Eq.(4) and the compensation reference currents ica *, icb * and icc * are obtained.

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = [T_{abc}] \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Where

$$[T_{abc}] = \frac{\sqrt{2}}{3}\begin{bmatrix} 1 & 0 & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

The calculated currents from Eq.(4) are the fundamental positive sequence reference supply currents, which meets the fundamental positive sequence load to maintain constant dc bus voltage. This ensures compensation of harmonics, reactive power and unbalancing. Hence different components in the load currents are extracted successfully using SRF theory. The source current is controlled to follow these reference fundamental positive sequence currents by switching the VSI through different control strategies like hysteresis current controller and sliding mode controller.

C. Hysteresis Current Control Method

The basic principal of the hysteresis control strategy is to compare the reference currents with the current produced by the inverter, the difference between them is compared to a fixed band called hysteresis band. As soon as the error reaches the lower band or higher a control command is send to the VSI in order to decrease or increase the output voltage of the inverter and maintain the error within the band surrounding the reference. Hence, Upper limit hysteresis band = Iref + max(Ic), Where I ref is the reference current. Lower limit hysteresis band= Iref – min (Ic) and Ic is the error current. As a result, the hysteresis bandwidth = Ic. Therefore the smaller the bandwidth, the better the accuracy.[9,10]

Hysteresis current control is a method of generating the required triggering pulses by comparing the error signal with that of the hysteresis band and it is used for controlling the voltage source inverter so that the output current is generated from the filter will follow the reference current waveform .

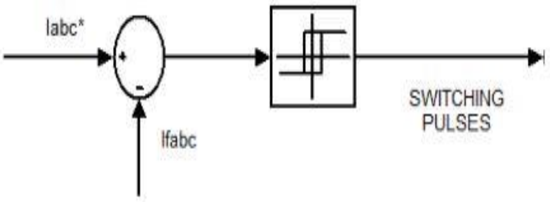

Fig 5: Hysteresis Band Current Controller

The ramping of the current between the two limits where the upper hysteresis limit is the sum of the reference current and the maximum error or the difference between the upper limit and the reference current and for the lower hysteresis limit, it is the subtraction of the reference current and the minimum error

D. Intelligent Current Control Techniques

The neural networks belong to the artificial intelligence techniques family, fuzzy logic, genetic algorithms. Artificial Neural network (ANN) is a connection of some artificial neurons which simulate a biological brain system. NN can train either offline or online when it is used in a system control. In [10], the ANN based current control of SAPF. The error signal is provided as an ANN input and ANN produces an appropriate switching signal for harmonic and reactive power compensation to the SAPF. In this method, a fixed switching frequency operation is achieved. In this control approach, the conventional controllers are replaced by the fuzzy controller, which possess two input and one output signal. The error (e) and its derivative (de) are used as the input to the fuzzy controller while the output is the command (Cde). The Intelligent Current Control methods do not require a model of SAPF; they need precise knowledge about operation and behavior of SAPF systems. [10] carried out a comprehensive analysis of current controllers.

IV. SIMULATION

A simulation study is done using MATLAB/SIMULINK to study the performance of shunt active filter based on d-q transformation and SRF theory. Simulation diagram is shown in fig 8, p-q control block is shown in fig 9 and SRF control block is shown in fig 10. The simulation parameters are illustrated in Table I.

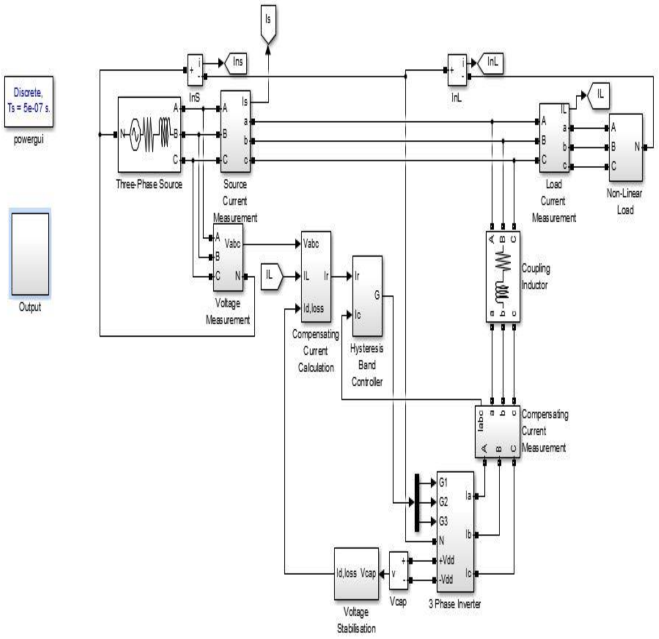

Fig 7: Simulation Diagram

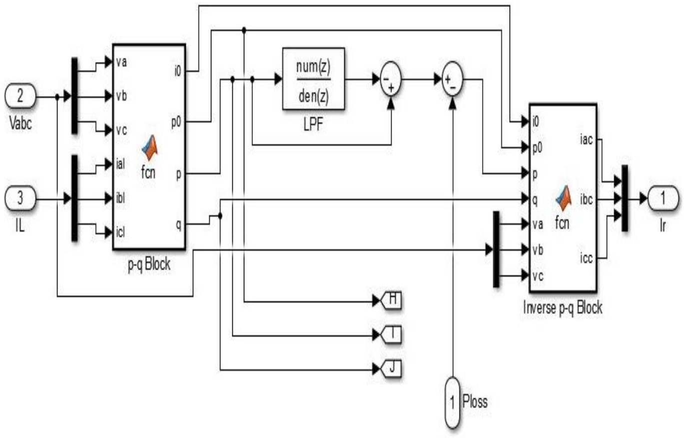

Fig 8 : Compensating Current Control using p-q Technique

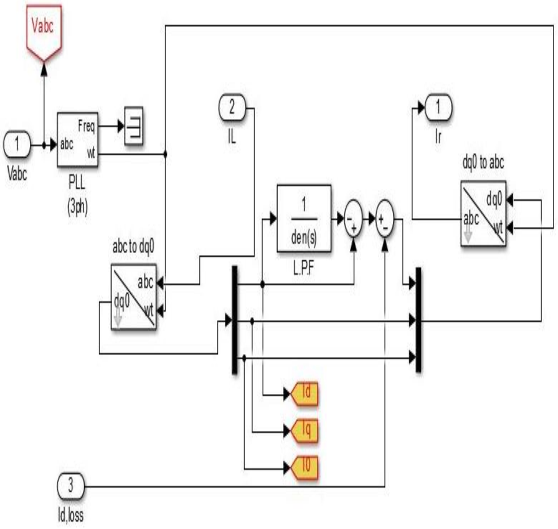

Fig 9: Compensating Current Control using SRF

Table 1: Simulation Parameters

Parameters	Values
Three phase source voltage (Vs))	415 V RMS, 50Hz
Filtering capacitor C1 & C2	4700x10^{-6} F
RL Branch	70Ω, 1.5H
RL Branch 1	60Ω, 1.3H
RL Branch 2	55Ω,1.1H

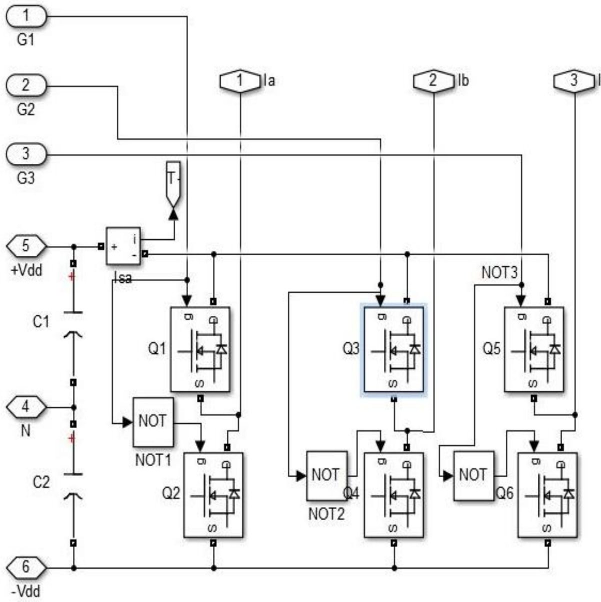

Fig 10: Three phase Inverter Block

The switches used in the simulation are IGBT switches. The output of the inverter is fed back at the input of the SPWM block for minimizing the error. Switches of the same leg are operated in a complimentary manner hence NOT gates are used shown in Fig.11. The three phase output from the inverter is injected into the system through a coupling inductor. The coupling inductor helps to suppress the high frequency components generated in the output due to the switching action of the switches

V. RESULTS AND DISCUSSION

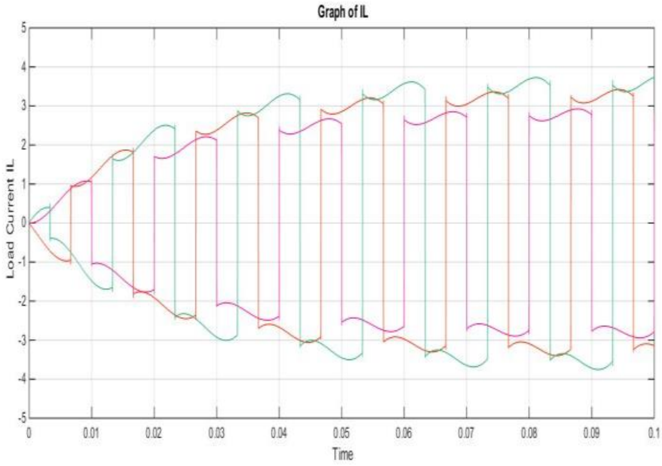

Fig 11: Graph of IL using dq0

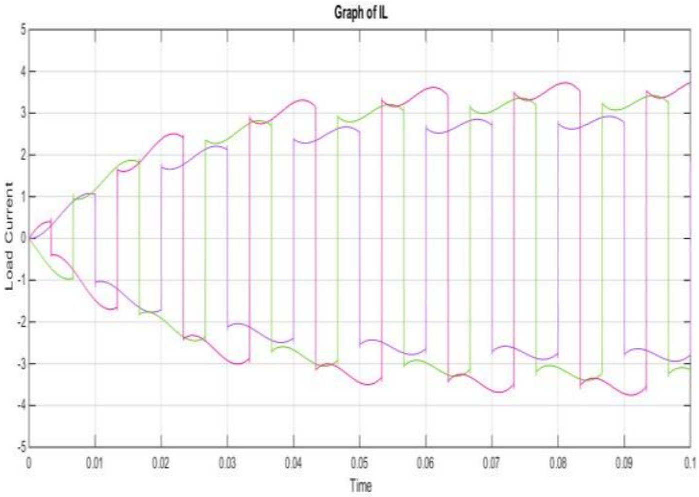

Fig 12: Graph of IL using SRF

In both cases (fig 11 &12) above, it is seen that load currents is being unbalanced with poor power factor and large harmonics.

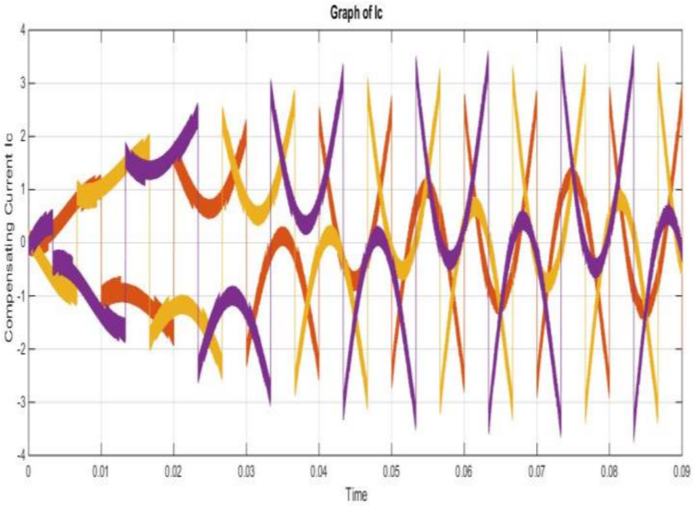

Fig 13: Compensating current (IL) using dq0

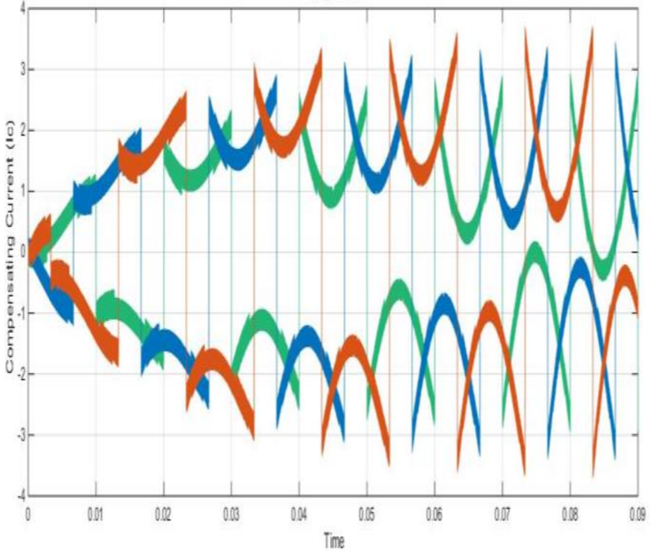

Fig 14: Compensating current using SRF

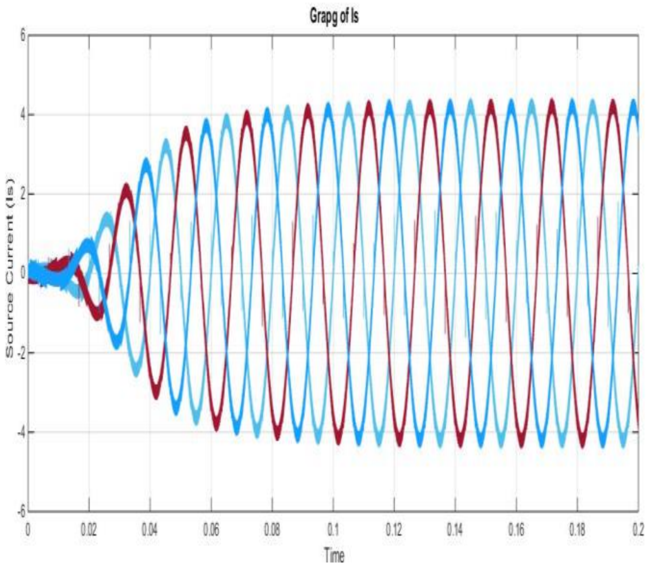

Fig 15: Source Current using dq0

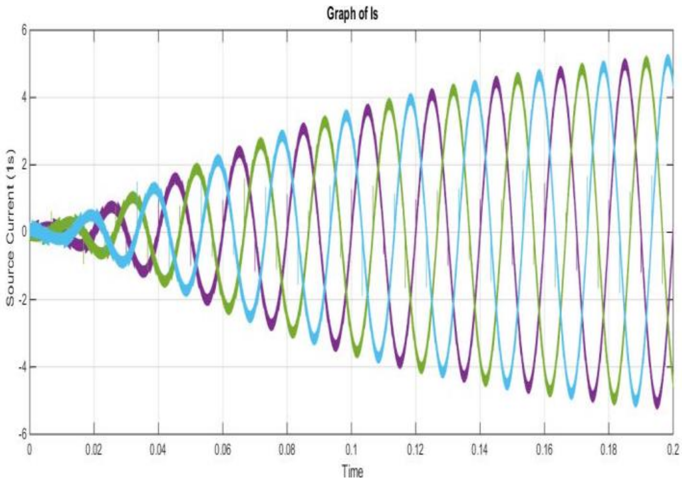

Fig 16: Source Current using SRF

SAPF makes source current sinusoidal as shown in the above figures for both cases by injecting appropriate compensating currents. It is seen that using dq0 technique, the three phases are sinusoidal and balanced at about 0.08sec as compared to using the SRF controller where stable time is about 0.14 sec.

As seen from the waveforms, the load current is purely non-sinusoidal square pulses with significant harmonic content. Fig 13 & 14 shows the compensating current generated by the VSI which includes harmonic content and reactive part drawn by the load. Because of the compensating current supplied by the inverter the source current as seen from the waveforms becomes sinusoidal.

VI. CONCLUSION

The principle of the shunt filter is to produce harmonic currents equal in magnitude but opposite in-phase to those harmonics that are present in the grid/source. In this paper, the study of various control techniques of the shunt active filter was done.

The actual implementation of p-q theory and synchronous reference frame theory in shunt active filters using the MATLAB software was carried out. Currents and voltages are taken as inputs to the filter from the line or load. The powers to be compensated are given as input. The compensator should draw exactly the given amount of current that produces the inverse of powers that are drawn by the load. Through transformation, we get the real and imaginary power values. By applying Inverse Clarke's transformation, we get the actual abc coordinates which can be applied to the line again.

Study and implementation of various control techniques of shunt active filters helps to mitigate power quality issues faced in electrical utilities. Also, soft computing techniques such as the fuzzy logic control can be further researched and implemented.

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