Harmonic Suppression System Using SRF and SIP Control Strategies

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Abstract- Three-phase four-wire distribution systems have been widely used in commercial and industrial installations. The neutral conductor carries the zero sequence current due to the unbalanced loading among the phase conductors. However, as electronic loads increases, their rectifier front-ends reduce significant harmonic current. The triplen harmonic current produced by these loads tends to accumulate in the neutral conductor due to its zero sequence nature, thus resulting in overloading of the neutral conductor and the distribution transformer. This paper proposes a new harmonic suppression scheme for the neutral conductors of three-phase four-wire distribution systems. In the proposed scheme, an active filter is connected in series with the neutral conductor and different schemes for phase conductors are also provided. The active filter operation will not affect the fundamental component due to the unbalanced loading, which the neutral conductor is sized for. The proposed scheme can eliminate current harmonics overloading on both the neutral conductor and the distribution transformer with only one active filter installation. The SIP control strategy based on Source Instantaneous Power for the shunt active filters is employed. Calculation of source instantaneous power is needed to determine instantaneous power component, which needs source currents and phase information so that the number of sensors can be reduced. The simulation results show that the output has low Total Harmonic Distortion (THD) value.

Key-Words: -Triplen Harmonic, Active filter, SRF, SIP, THD.

1. INTRODUCTION

Power electronics have grown tremendously in recent years. These power electronic systems offer highly non-linear characteristics. An increase in such non-linearity causes various undesirable features such as increased harmonics and reactive power components of current from AC mains, low system efficiency and a poor power factor. These harmonics producing loads contribute to the degradation of power quality in transmission and distribution systems. They also cause disturbance to other consumers and interference in nearby communication networks.

The increased severity of harmonic pollution in power networks with the development of power semiconductors and power electronics application techniques has attracted the attention to develop dynamic and adjustable solutions to the power quality problems. There are large number of publications covering the power quality survey, measurements, analysis, cause and effect of harmonics and reactive power in the electrical networks.

In order to overcome these problems, active filters have been developed. The traditional method of current harmonic reduction involves passive filters connected in parallel to the grid. Under normal operating conditions with reasonably balanced load, the current in the neutral is expected to be 20% of the normal phase currents. These neutral currents are fundamentally third harmonics and odd multiples of 3rd due to non-linearity of loads. In recent years, SAPFs based on voltage controlled PWM converters have been investigated and recognized as a viable solution. This harmonic suppression can be done with the help of SERIES ACTIVE POWER FILTERS and HYBRID ACTIVE POWER FILTERS. This active filter is connected in series with the neutral line and also in phase conductor to reduce the harmonics in the line.

2. HARMONICS AND ITS SOLUTION METHODOLOGIES

2.1 Harmonics

Harmonics can be defined as a sinusoidal component of a periodical waveform having a frequency that is an integral multiple of a fundamental frequency. Harmonics are classified into even harmonics and odd Harmonics Even harmonics are generated due to the uneven current drawn between the positive and negative halves of one cycle of operation. Odd harmonics have odd numbers and the majority of non-linear loads produce the harmonics that are odd multiples of the fundamental frequency. If the fundamental frequency is 50 Hz, then the 3rd order harmonics will have a frequency of 150 Hz, 5th order harmonics will have a frequency of 250 Hz and so on. When switching action takes place in asynchronous ac-dc-ac links, transient occurs contributing to higher order harmonics. The voltage fluctuations in computer power supplies gives rise to harmonics which severely affects the supply levels. Fluorescent lamps are one of the common sources of harmonics in the home applications.

2.2 Effect of Harmonics

The effects of harmonics in the power electronics applications are listed below,

- Increase in loses and consequent heating of transformer and rotating machines.
- Leads to increase in losses in power system.
- Increased errors in energy meter, Produces telephone interference.
- Malfunctioning of protective devices.

Non-linear loads draw current only during a controlled portion of the incoming voltage waveform. While this dramatically improves efficiency, it causes harmonics in the load current. These harmonics, in turn, can lead to overheating of power transformers and neutrals, as well as tripped circuit breakers. The proliferation of microelectronics processors in a wide range of equipments, from home VCRs and digital clocks to automated industrial assembly lines and hospital diagnostics systems has increased the vulnerability of such equipment to power quality problems.

2.3 Types of Harmonics

Harmonics are classified into following two types,

1. Characteristic harmonics
2. Non-Characteristic harmonics

The characteristics harmonics are the harmonics, which are always present even under ideal operation condition. Semiconductor equipments in the course of normal operations also produce these harmonics. The harmonics of the order other than characteristic harmonics are termed as non-characteristic harmonics. These harmonics are less predominant. These occur due to an unbalance operation in the power systems.

2.4 Types of Filters used for Harmonic Suppression

Filters are used to limit the flow of harmonic currents in the power systems. There are three basic types of filters namely,

- Passive Filters
- Active Filters
- Hybrid Filters.

Passive Filters consist of passive elements and which is the simplest method of harmonic filtering. It uses the reactive storage components, namely capacitors and inductors. It has two types, namely Shunt Passive and series Passive Filter. Active Filters are emerging devices for harmonic filtering and which uses Controllable Sources to neutralize the harmonics in the Power Systems. The basic principle of operation of an Active Filter is to inject a suitable non-sinusoidal voltage and currents into the system in order to achieve a clean voltage and current waveforms at the point of filtering. Hybrid Filter consists of both an active filter and a passive filter. In certain cases it could be a cost effective solution. The passive filter carries out basic filtering and the active filter through its precise dynamic behavior covers the other harmonic orders.

3. POWER ACTIVE FILTERS AND ITS CONTROL STRATEGIES

3.1 Introduction

In recent years, the development of Power Electronics Technology and its applications are wide in nature, which leads to the serious harmonic pollutions. These kinds of harmonics can be eliminated by using Power Active Filtering technology and its control strategies are explained below.

Active filters have become a viable alternative for controlling harmonic levels in industrial and commercial facilities. However, there are many different filter configurations that can be employed and there is no standard method for rating the active filters. More advanced solutions include active filters, which inject compensation current onto the system to ‘cancel out’ a major portion of the harmonic currents. Due to an active filter’s low impedance, loads connected draw more harmonic current than would be the case with no active filter in circuit.

3.2 Series Active Power Filter

The series active filter is connected in series with the neutral conductor to suppress the harmonics, which often suppresses the harmonics in the phase conductor as well. And to increase the effectiveness of filter in the phase conductor, a series filter will be included in the circuit. The development of new Series Active Filtering technology and the design of different controllers are represented in this chapter.

3.2.1 Series Filter scheme using RUV method

Three phase bridge rectifier with RC loads (non-linear loads) are connected to the three phase four wire distribution systems. Due to the nature of the non-linear loads, harmonics are injected into the system through the neutral currents. This harmonics are injected into the phase conductors as well. Series Active Power Filter is connected in neutral conductor to suppress the harmonics. The Voltage Source Inverter (VSI) generates a compensating harmonics currents into the neutral conductor through the inductor and capacitor sets connected in series with it. The generated harmonic currents and the harmonic currents flowing in the neutral conductor cancel each other without affecting the fundamental part of the neutral current.

3.2.2 Model of RUV Controller

An active filter is connected in series with the neutral conductor of the three-phase four-wire system. A Hall-Effect sensor provides the measurement of the neutral current in the system controller. The measured neutral current I_n from the system containing both harmonic and fundamental components is multiplied by $\sin(\omega_o t)$ and $\cos(\omega_o t)$ respectively, to extract the fundamental components of I_n, where ω_o is the frequency of the utility grid.

The fig. 3.2 shows the control block diagram of the proposed Active Power Filter.

The fundamental components of I_n is converted into DC and the harmonics are converted into AC after the multiplication process. $\text{Sin}(\omega_o t)$ and $\text{Cos}(\omega_o t)$ are synchronized to the utility by a Phase-Lock-Loop (PLL) circuit. The Voltage command of the active filter inverter is generated by,

$V_{inv} = K_h.(I_n-I_{n,f}) = K_h.$

where, $I_{n,h}$ represents the harmonic components.

V_{inv} represents a high gain (K_h).

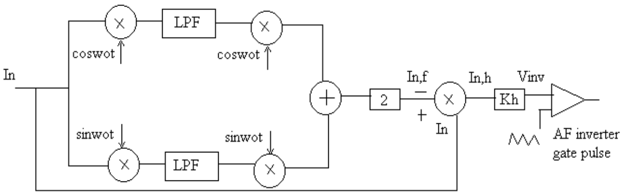

Fig. 3.1 Control block diagram for RUV method

The Voltage component V_{inv} is compared with the triangular carrier wave to generate the PWM gating pulse. The active filter inverter switches at 20 KHz to provide sufficient bandwidth for the desired filtering characteristics. Depending upon the PWM gating pulses, the inverter circuit will inject the negative harmonic currents to the neutral line. As a result, only fundamental components of the neutral current will flow through the line.

3.2.3 Series Filter scheme using SRF method

The Active Filter configuration discussed in this thesis is based on a Pulse Width Modulated (PWM) voltage source inverter that interfaces with the system through a system interface filter. Usually, the Filter is connected in Series with the load being compensated. Therefore, the configuration is often referred as series active filter. The voltage source inverter used in the active filter makes the harmonic control possible. This inverter uses dc capacitors as the supply and can switch at a high frequency to generate a signal which will cancel the harmonics from the nonlinear load. Use active switching components, only one filter needed to eliminate all the unwanted harmonics, and which is also used for power factor correction.

3.2.4 Model of SRF Controller

To determine reference sinusoidal source currents at the fundamental Frequency, the load current in the a-b-c reference frame is transformed into the stationary reference frame according to equation 4.1.

$$\begin{bmatrix} i^s{}_q \\ i^s{}_d \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{la} \\ i_{bl} \\ i_{lc} \end{bmatrix} \quad \text{...(4.1)}$$

Next, the stationary reference frame quantities are transformed into synchronous reference frame quantities at fundamental frequency by using equation 4.2, where θ is the angular position of the synchronous reference frame.

$$\begin{bmatrix} i^e{}_q \\ i^e{}_d \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i^s{}_q \\ i^s{}_d \end{bmatrix} \quad \text{...(4.2)}$$

The dc current components of equation (4.2), $i^e{}_q$ and $i^e{}_d$ are extracted via low-pass filters and are transformed back into stationary reference frame by equation 4.3.

The fundamental components of the load currents in the a-b-c reference frame are determined according to equation 4.4, which will be the desired source currents.

$$\begin{bmatrix} i^1{}_{la} \\ i^1{}_{lb} \\ i^1{}_{lc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} * \begin{bmatrix} i^s{}_{qd} \\ i^s{}_{dd} \end{bmatrix} = \begin{bmatrix} i^*{}_{sa} \\ i^*{}_{sb} \\ i^*{}_{sc} \end{bmatrix} \quad \text{...(4.4)}$$

Therefore, the APF reference compensation currents can be obtained by subtracting the fundamental components computed in equation (4.4) from the load currents.

The model for the synchronous reference frame method is shown in below Fig. 3.4

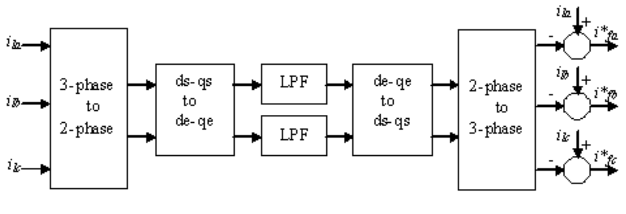

Fig. 3.2 Model of SRF Controller

3.3 Hybrid Active Power Filter

The general block diagram for hybrid filter scheme using Synchronous Reference Frame method was shown above, and this strategy is mostly used for Phase conductors. The hybrid filter block is nothing but the combination of series active filter and passive filter. As like earlier method the Series Active Filter is connected in series with phase conductor and Passive Filter is connected in parallel. The Passive Filter is the combination of Inductance and Capacitance, which suppresses the fifth and seventh harmonics.

$$\begin{bmatrix} i^{s}{}_{qd} \\ i^{s}{}_{dd} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i^{e}{}_{qd} \\ i^{e}{}_{dd} \end{bmatrix} \qquad ...(4.3)$$

With a large gain K_h, the active filter inverter emulates high resistances at the harmonic frequencies. Therefore the harmonic components of the neutral current I_n can be suppressed. Hybrid Active Filters are more suitable for non-linear loads characterized by harmonic voltage source, such as diode rectifier with smoothening DC bus capacitors.

3.4 Shunt Active Power Filter

3.4.1 General block diagram

The three phase Shunt Active Power Filter (SAPF) that implements PWM converter connected in parallel with three phase three wire or four wire non-linear load using a control method that is based on Source Instantaneous Power (SIP). This shunt active power filter will inject compensation currents to make the source currents nearly sinusoidal with unity power factor. Application of this APF in four wire system will reduce neutral current. To apply the proposed control method, it needs source current quantities and APF's phase information that is used to make three phase sinusoidal waveforms with constant amplitude and in phase with respect to source voltages (representative source voltages).

3.4.2 Principle of Shunt Active Filter

The performance of the active power filter is to inject the compensation current to the power feeder, in order that the current supplied from the mains is nearly a sine wave and in phase with the source voltage, irrespective of the waveform of the load current. The following equations describe the procedure that is used to derive the fundamental component of the load current:

3.4.3 Model of SIP Controller

Fig. 4.1 shows the scheme of SIP based control method. Detecting source currents and using abc-αβ0 transformation will result in source currents in αβ0−axes

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ i_{so} \end{bmatrix} = \begin{bmatrix} T_{abc-\alpha\beta o} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \qquad \ldots\ldots (4.5)$$

where i_α, i_β, i_0 are phase currents in the 'αβ0' co-ordinates and i_a, i_b, i_c are phase currents in the 'abc' co-ordinates

The representative voltages which are unity amplitude three-phase sinusoidal waveforms are obtained by using phase information and PLL (Phase Locked Loop). These can be expressed in αβ-axes as,

$$\begin{bmatrix} v_{\alpha\_r} \\ v_{\beta\_r} \end{bmatrix} = \begin{bmatrix} \sin\omega t \\ -\cos\omega t \end{bmatrix} \qquad \ldots\ldots (4.6)$$

This condition always causes the calculated instantaneous power contain no zero-sequence power. So this control method is capable to be used in systems with or without neutral wire.

The source instantaneous power is determined by using,

$$\begin{bmatrix} p_S \\ q_S \end{bmatrix} = \begin{bmatrix} v_{\alpha\_r} & v_{\beta\_r} \\ -v_{\beta\_r} & v_{\alpha\_r} \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} . \ (4.7)$$

By decomposing the source instantaneous power into,

$$\begin{bmatrix} p_S \\ q_S \end{bmatrix} = \begin{bmatrix} \overline{p}_S + \widetilde{p}_S \\ \overline{q}_S + \widetilde{q}_S \end{bmatrix} \qquad \ldots\ldots (4.8)$$

and filter out the dc component of the source instantaneous real power p_s will produce undesired source instantaneous power. Inversed calculation is done to obtain undesired currents of the source as,

$$\begin{bmatrix} i^{**}_{s\alpha} \\ i^{**}_{s\beta} \end{bmatrix} = \begin{bmatrix} v_{\alpha\_r} & v_{\beta\_r} \\ -v_{\beta\_r} & v_{\alpha\_r} \end{bmatrix}^{-1} \begin{bmatrix} \widetilde{p}_S \\ \overline{q}_S + \widetilde{q}_S \end{bmatrix} \qquad \ldots..(4.9)$$

From equation (4.6), there are three current components which are obtained by inversed calculation. It indicates that there is no influence of zero sequence power and it is right for systems without neutral wire but there is a problem in systems with neutral wire. Therefore, adding zero sequence current in transforming αβ0 into abc.

This SIP based control method will always make undesired currents in (4.6) equal to zero. If this requirement is achieved so , the source side only creates current components caused by dc component of source instantaneous real power, these type of currents are named active currents i_s* which are in phase with respect to main voltages and have fundamental frequency.

$$\begin{bmatrix} i^{**}_{sa} \\ i^{**}_{sb} \\ i^{**}_{sa} \end{bmatrix} = \begin{bmatrix} i^{**}_{sa\_ph} + i^{**}_{sa\_qf} + i^{**}_{sa\_qh} + i^{**}_{sa\_o} \\ i^{**}_{sb\_ph} + i^{**}_{sb\_qf} + i^{**}_{sb\_qh} + i^{**}_{sb\_o} \\ i^{**}_{sc\_ph} + i^{**}_{sc\_qf} + i^{**}_{sc\_qh} + i^{**}_{sc\_o} \end{bmatrix} \qquad \ldots\ldots (4.10)$$

4. FILTER DESIGN

4.1 Design of Series Active Filter

4.1.1 Block diagram for proposed scheme

In this system, the three phase source is connected to the load through a rectifier (Non linear load). Due to the presence of rectifier load in the system, the harmonics are injected into the phase line as well as the neutral line. In order to reduce the harmonics in the phase line as well as in the neutral line, the hybrid active filter is connected in series with each phase through the series coupling transformer.

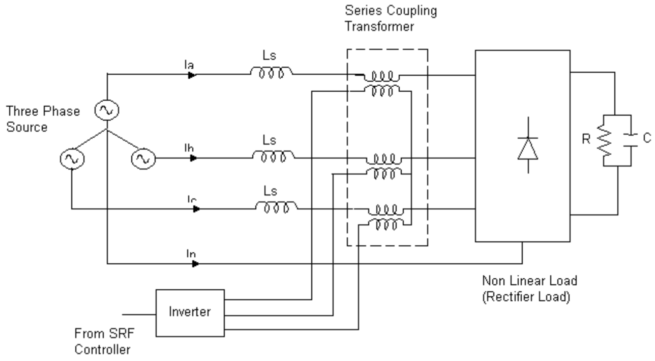

Fig. 4.1 Proposed Scheme of Series Active Filter

4.1.2 Circuit diagram

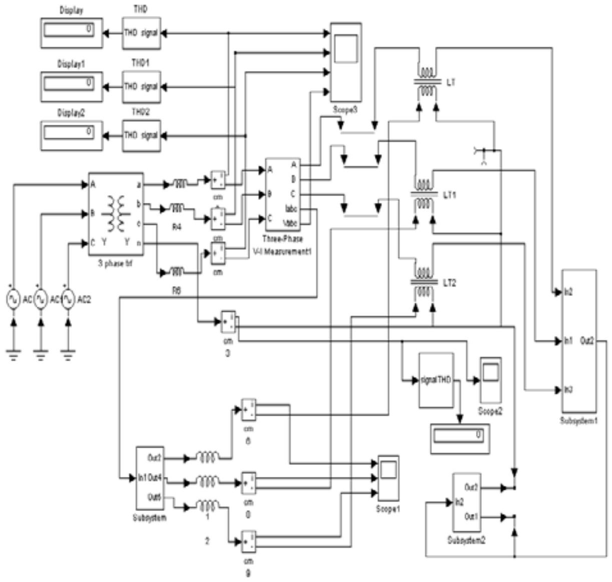

Fig 4.2 Matlab model for Series Filter scheme with Neutral Filter

4.1.3 Simulation Results

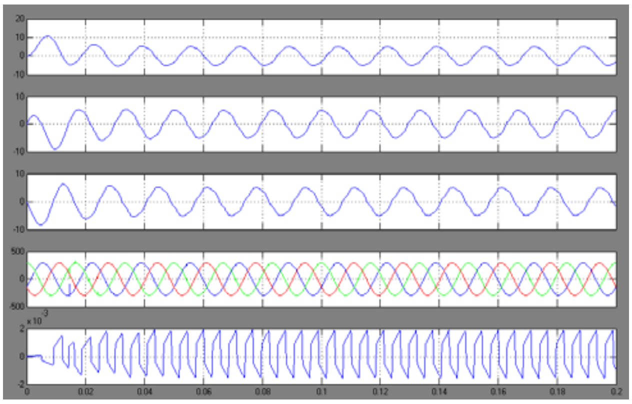

Fig 4.3 Waveform for R load without neutral Filter

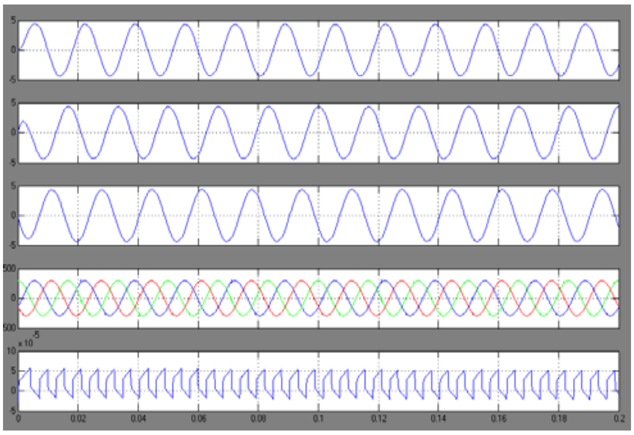

Fig 4.4 Waveform for R load with neutral Filter

4.2 Design of Hybrid Active Filter

4.2.1 Block diagram for proposed scheme

A series active filter consists of three leg voltage source inverter which is controlled by the Synchronous Reference Frame controller. Based on the SRF controller output, the inverter will inject the negative harmonic current in the line, which leads to the cancellation of the harmonics in the line. The Hybrid active filter consists of passive components (L and C), which suppresses the 5th and 7th order harmonics.

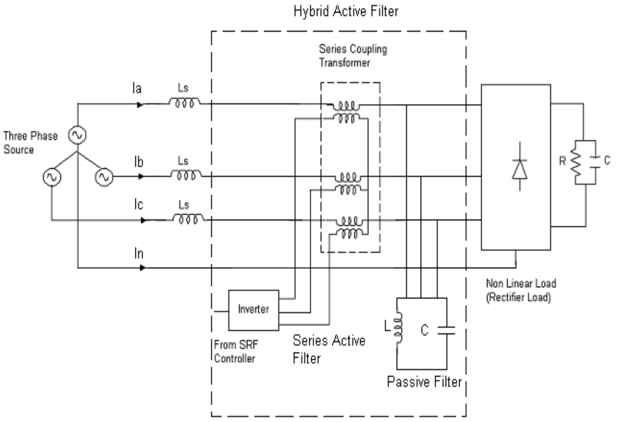

Fig. 4.5 Proposed Scheme of Hybrid Active Filter

4.2.2 Circuit diagram

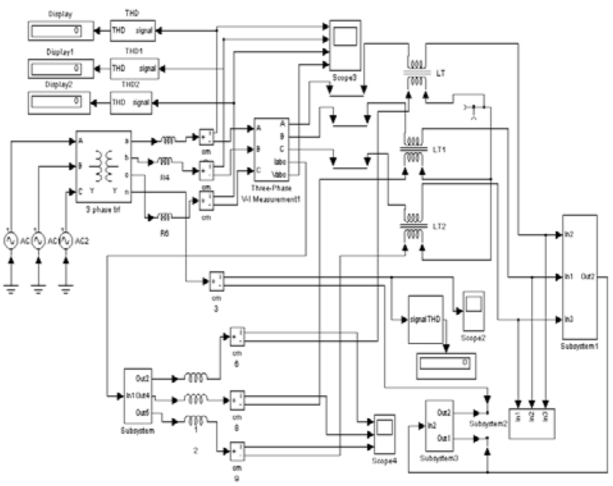

Fig 4.6 Matlab model for Hybrid Filter scheme with neutral Filter

4.2.3 Simulation Results

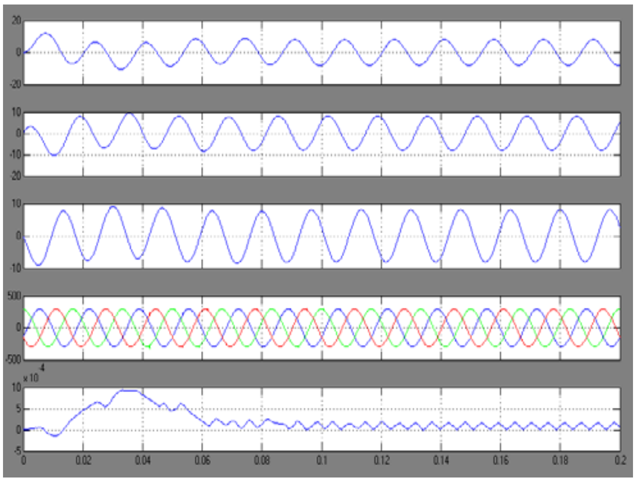

Fig. 4.7 Waveform for R load without neutral Filter

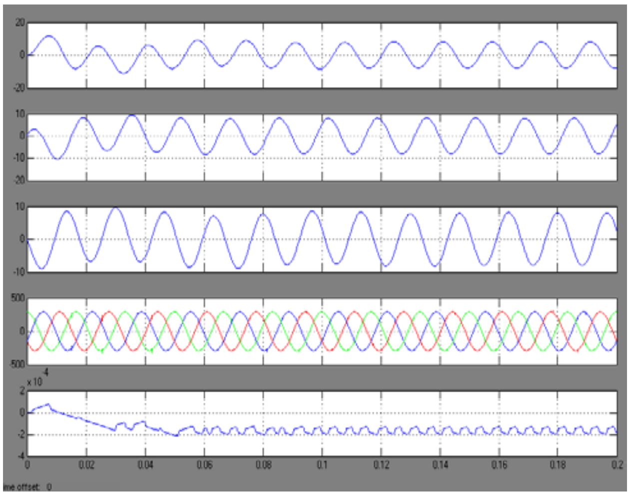

Fig. 4.8 Waveform for R load with neutral Filter

4.3 Design of Shunt Active Filter

4.3.1 Circuit diagram

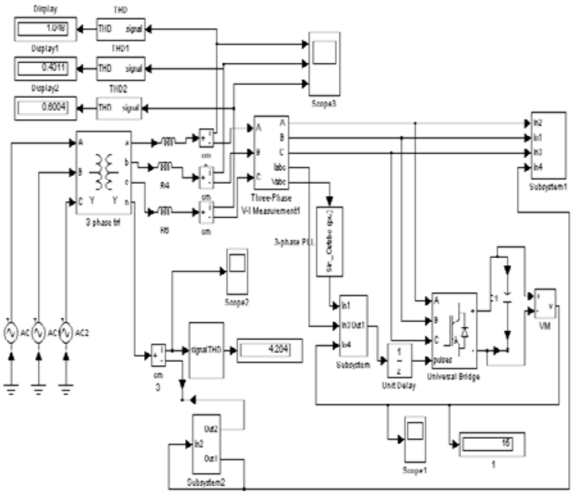

Fig 4.9 Matlab model for Hybrid Filter scheme with neutral Filter

4.3.2 Simulation Results

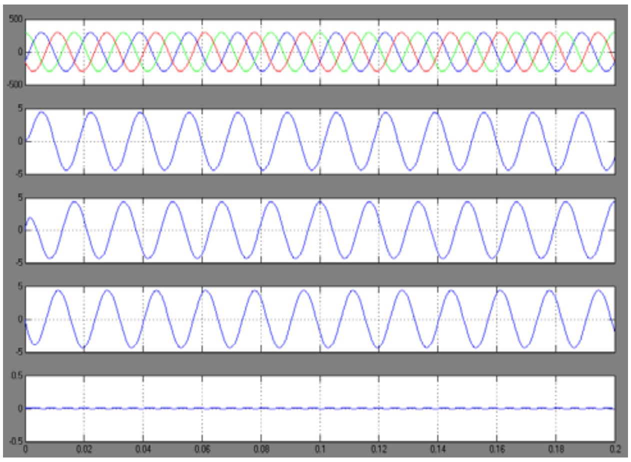

Fig 4.10 Waveform for RL load without neutral Filter

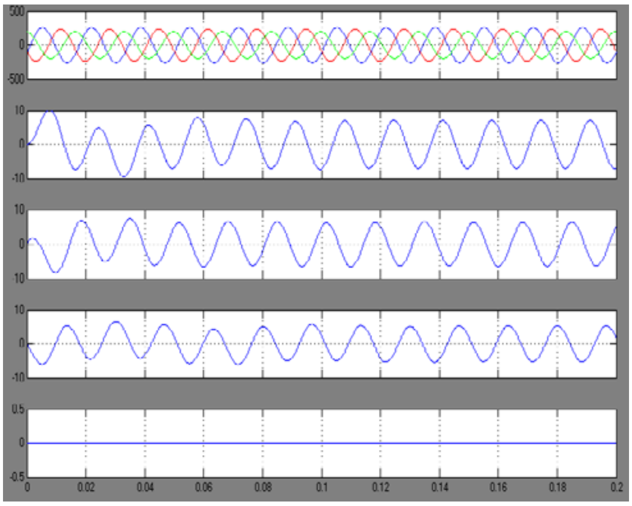

Fig 4.11 Waveform for RL load with neutral Filter

4.4 Comparative Analyis of Various Active Filters Under Different Loads

The tabulation 4.2 shows the THD values of series, shunt and hybrid active filters under different load cases.

TYPE OF FILTERS	WITHOUT NEUTRAL FILTER		WITH NEUTRAL FILTER	
	R-LOAD	RC-LOAD	R-LOAD	RC-LOAD
SERIES ACTIVE	9.167	10.36	4.938	7.321
SHUNT ACTIVE	5.839	7.67	3.142	4.264
HYBRID ACTIVE	7.093	8.187	2.878	5.081

Table 4.4.1 THD values for different types of Filters

From the above tabulation, it is inferred that Hybrid Active Filter performed well, in comparison to Series and Shunt Active Filters.

4.4.1 Discussion about percentage reduction in THD values

- For RC Load, by using Series Active Power Filter the THD value is decreased around 29.4%.
- For RC Load, by using Shunt Active Power Filter the THD value is decreased around 32.19%.
- For RC Load, by using Hybrid Active Power Filter the THD value is reduced around 37.83%.

5. CONCLUSIONS

The primary objective of this paper is to model and develop the proposed new Series Active Power Filter, Hybrid Active Filter and Shunt Active Power Filter using Synchronous Reference Frame (SRF) and Source instantaneous power (SIP) Controller for the current harmonics suppression in three phase four wire system using MATLAB simulation tool. The model of the proposed new Series Active Power Filter, Hybrid Active Filter and Shunt Active Power Filter is realized. The developed Series Active Power Filtering technology and Hybrid Active Filtering technology is implemented for a system feeding a non-linear load. Calculation of source instantaneous power is needed to determine instantaneous power component that may not be created by the source. This calculation only needs source currents and phase information so the amount of sensors can be minimized.

- By using Series, Shunt and Hybrid Active Power Filters, their performances for different types of loads are analyzed and they decrease the THD values around 29.4%, 32.19%, 37.83%.
- It is inferred that Hybrid Active Filter is performed well, in comparison to Series and Shunt Active Filters.

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