Comparison of Control Algorithms for Shunt Active Filter for Harmonic Mitigation

A.Giri Prasad[1] ,K.Dheeraj[2] ,A.Naveen Kumar[3],
Electrical and Electronics Engineering Department
ST.Peter's Engineering college, Kompally, Hyderabad

Abstract:- Shunt Active Filter generates the reference current, that must be provided by the power filter to compensate harmonic currents demanded by the load. This paper presents different types of SRF methods for real time regeneration of compensating current for harmonic mitigation. The three techniques analyzed are the Synchronous Reference Frame Theory (SRF), SRF theory without synchronizing circuit like phase lock loop (PLL) also called instantaneous current component theory and finally modified SRF theory. The performance of Shunt Active Power Filter in terms of THD (Total Harmonic distortion) of voltage and current is achieved with in the IEEE 519 Standard. The comparison of all methods is based on the theoretical analysis and simulation results obtained with MATLAB/SIMULINK

Index terms—*Synchronous Reference Frame, instantaneous current component theory, Modified SRF, Active Filter, Harmonics.*

I. INTRODUCTION

The increasing use of power electronic based loads (adjustable speed drives, switch modern power supplies, etc) to improve system efficiency and controllability is increasing concern for harmonic distortion levels in end use facilities and on overall power system. The Active Power Filter uses power electronic switching to generate harmonic currents that cancel harmonic content from non – linear loads. Over the recent years, power quality has been given attention due to the intensively use of power electronic Controlled applications in all branches of industry, such as controlling or converting AC power to feed electrical loads.

The non-linear loads have led to the concerns over the allowable amounts of harmonic distortion injected into the supply system. Standards such as IEEE-519 have emerged to set and impose limits and recommended practices so that the harmonic distortion levels are kept in check, thereby promoting better practices in the design and operation of power system and electric equipment.

Based on observations from various references, a practical limit of less than 5% of the total harmonic distortion(THD) must be employed by any system designers and/or end-users to ensure compliance with the established standards. Many efforts have been expended to develop active power filters and conditioner that can soften the power quality problems.

One of the cornerstones of the active filter is its control strategy that is implemented in the active filter controller. The performance of an active filter depends mainly on the selected reference generation scheme.

The control strategy for a shunt active power filter generates the reference current, that must be provided by the power filter to compensate reactive power and harmonic currents demanded by the load. This involves a set of currents in the phase domain, which will be tracked generating the switching signals applied to the electronic converter by means of the appropriate closed-loop switching control technique such as hysteresis or deadbeat control.

Several methods including instantaneous real and reactive power theory have been proposed for extracting the harmonic content. This paper presents a different modification based on the same principle and compares its performances with sinusoidal source and balanced load condition. The Modified SRF method called, in this paper, Filtered Modified Reference Frame Method (FMRF), because it uses filters and is based on the modified reference frame method .

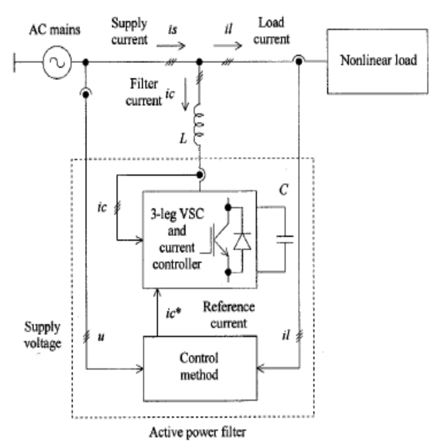

Fig. 1: Basic principal of shunt current compensation in active

II. SRF METHODS

Among the several methods presented in the literature, the Synchronous Reference Frame method (SRF) is one of the most common and probably it is widely used method. This section is organized as to describe succinctly the SRF methods. The three methods presented in this section with some results obtained with the above mentioned methods. The nonlinear load considered is a three-phase diode bridge rectifier.

A. Synchronous Reference Theory (SRF)

In the SRF, the load current signals are transformed into the conventional rotating frame d-q. If θ is the transformation angle, The transformation is defined by:

$$\begin{bmatrix}x_d\\x_q\\x_0\end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix}\cos(\theta) & \cos\left(\theta-\frac{2\pi}{3}\right) & \cos\left(\theta-\frac{4\pi}{3}\right)\\ -\sin(\theta) & \sin\left(\theta-\frac{2\pi}{3}\right) & -\sin\left(\theta-\frac{4\pi}{3}\right)\\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}\end{bmatrix}\begin{bmatrix}x_a\\x_b\\x_c\end{bmatrix} \qquad (1)$$

Where x denotes voltages or currents.

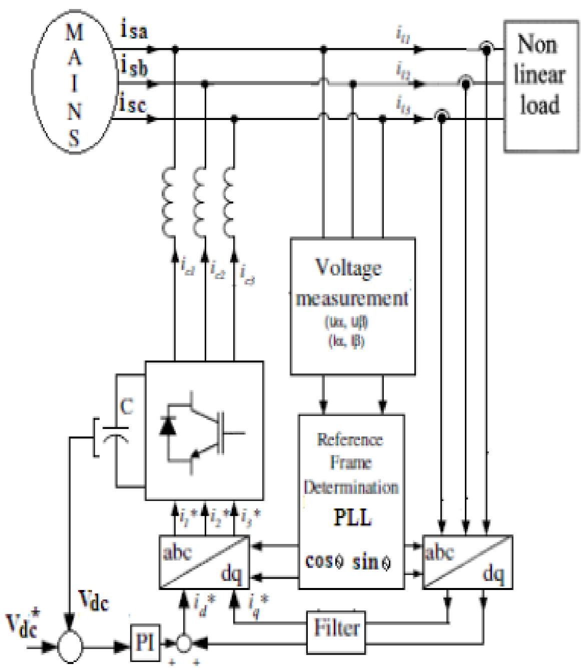

Fig. 2: Basic Synchronous Reference Frame Configuration

In the SRF θ is a time varying angle that represents the angular position of the reference frame which is rotating at constant speed in synchronism with the three phase ac voltages. To implement the SRF method some kind of synchronizing system should be used. In phase-locked loop (PLL) is used for the implementation of this method. In this case the speed of the reference frame is practically constant, that is, the method behaves as if the reference frame's moment of inertia is infinite. The fundamental currents of the d-q components are now dc values. The harmonics appear like ripple. Harmonic isolation of the d-q transformed signal is achieved by removing the dc offset. This is accomplished using high pass filters (HPF). In spite of a high pass filter, a low pass filter is used to obtain the reference source current in d-q coordinates. Fig 2 illustrates a configuration of the SRF method. There is no need to supply voltage waveform for a SRF based controller. However the phase position angle must be determined using voltage information. The SRF harmonic detection method can be reasonably summarized as a block diagram as shown in Fig.3.

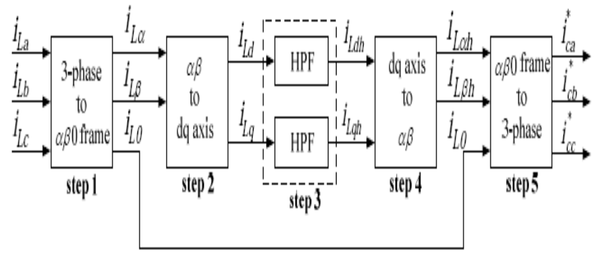

Fig.3: SRF harmonic detection

B. Instantaneous Current Component (id-iq) Theory:

Fig.1 shows the schematic block diagram of the shunt active filter with controller. The block diagram consists of variable sensing system, Reference Estimation System, PWM signal generator and system controller.

The variable sensing block senses the system variables like supply current, load current and compensating current, DC link voltage or current. PWM signal generator and system controller generate switching signals for converter switches based on the error produced by reference signal and actual system variables.

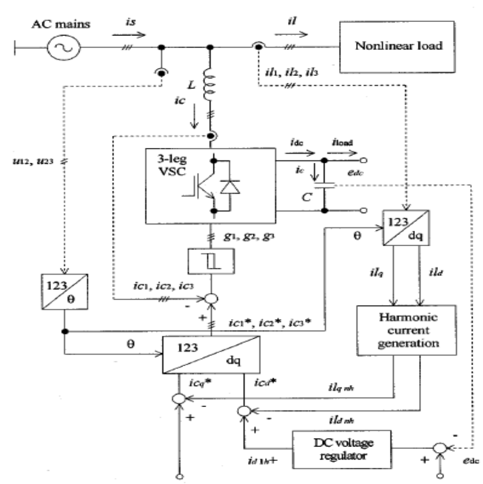

Fig.4: AF control system based on the instantaneous active and reactive current component Id - Iq method.

In this method the currents I_{ci} are obtained from the instantaneous active and reactive current components Iℓd and Iℓq of the nonlinear load. In the same way, the mains voltages v_i and the polluted currents Iℓi in αβ as in the previous method by 2 and 3. However, the load current components are derived from a synchronous reference frame based on the Park transformation, where represents the instantaneous voltage vector angle 4

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} il_\alpha \\ il_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} il_1 \\ il_2 \\ il_3 \end{bmatrix}$$

… (3)

$$\begin{bmatrix} il_d \\ il_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} il_\alpha \\ il_\beta \end{bmatrix}, \quad \theta = \tan^{-1}\frac{u_\beta}{u_\alpha}. \quad (4)$$

With transformation the direct voltage component is $u_{dq}=u_{\alpha\beta}=$ $|\bar{u}_{dq}| = |\bar{u}_{\alpha\beta}| = \sqrt{u_\alpha^2 + u_\beta^2}$ and the quadrature voltage component is always null, Uq=0 , so due to geometric relations 4 becomes

$$\begin{bmatrix} il_d \\ il_q \end{bmatrix} = \frac{1}{\sqrt{u_\alpha^2 + u_\beta^2}} \cdot \begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix} \cdot \begin{bmatrix} il_\alpha \\ il_\beta \end{bmatrix}. \quad \ldots\ldots\ldots(5)$$

Instantaneous active and reactive load currents Iℓd and Iℓq can also be decomposed into oscillatory and average terms Iℓd=I*ℓd+Iℓd , and Iℓq=I*ℓq+Iℓq . The first harmonic current of positive sequence is transformed to dc quantities, $i\ell^{+}_{dq1h}$ i.e., this constitutes the average current components. All higher order current harmonics including the first harmonic current of negative sequence, $\tilde{il}^{\pm}_{dqnh} + \tilde{il}^{-}_{dq1h}$, are transformed to non-dc quantities and undergo a frequency shift in the spectra, and so, constitute the oscillatory current components. These assumptions are valid under balanced and sinusoidal mains voltage conditions. Eliminating the average current components by HPF's the currents that should be compensated are obtained, $ic_d = -\tilde{il}_d$ and $ic_q = -\tilde{il}_q$.

$$\begin{bmatrix} ic_\alpha \\ ic_\beta \end{bmatrix} = \frac{1}{\sqrt{u_\alpha^2 + u_\beta^2}} \cdot \begin{bmatrix} u_\alpha & -u_\beta \\ u_\beta & u_\alpha \end{bmatrix} \cdot \begin{bmatrix} ic_d \\ ic_q \end{bmatrix} \quad (6)$$

C. Modified (id-iq) Theory

The method suggested in this section is based on the modified (i_d-i_q) method (FMRF). The principle is the same. However there are two differences in the determination of the instantaneous position of the rotating reference frame. In spite of using the αβ voltages to calculate the transformation angle, low pass filters (LPF) are used to reduce harmonics of the network signals, and consequently use on the control process approximate sinusoidal waveforms, "fig.6".

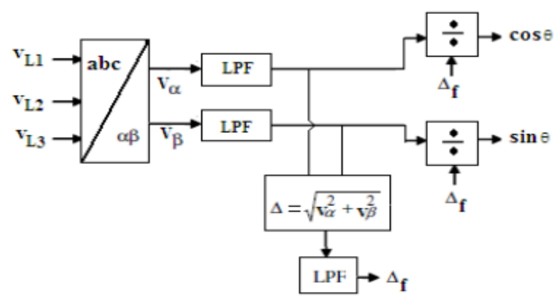

Fig. 5: Principal of modified (id-iq) method

The second modification consists in separating the Δ coefficient and to use a filtered Δ coefficient. This new modification is important because the system will presents better results to inverse sequence components. These concepts are presented in "fig. 5" using block diagrams. The modified synchronous reference frame method has excellent results in balanced sinusoidal and unbalanced ac mains.

In all cases studied in this paper, the load is a three phase diode bridge with an inductive circuit on its dc side. The LPF_α, LPF_β (cutoff frequency f_c) and LPF_Δ (cutoff frequency f_d) have different functions. Filters LPF_α, LPF_β are set to filter the ac mains and to avoid the influence of voltage harmonics presented on the network point of common coupling. The LPF_Δ is set to avoid the oscillation of the Δ parameter that is due to the inverse sequence component. The low pass filter used for LPF_α, LPF_β, and LPF_Δ, the type of LPF are of 4th order Butterworth and 1st order chebyshev type with appropriate cutoff frequencies. In this method the cutoff frequency of the Δ filter was set at 8 Hz and the cutoff frequency of the alpha and beta filters were also set to 60 Hz in Butterworth filter and passing band frequency of 20 Hz is used in chebyshev type of LPF.

III RESULTS AND ANALYSIS

In order to evaluate the performance of all the methods simulation studies are carried out. In FMRF method it is observed that the supply current is close to sinusoidal and it remains in phase with the supply voltage, therefore, unity power factor is maintained at the output of supply system. From the figures 6 to 17 are results corresponding the three SRF Theories and Comparison is shown in the Table 1

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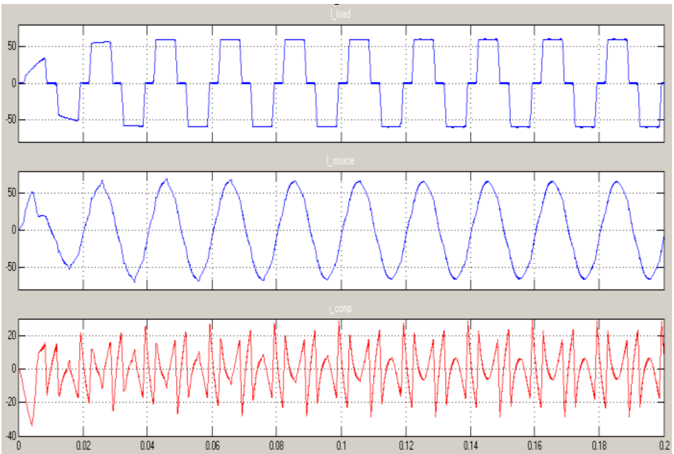

Fig 6: Performance of SRF theory: (1) Load current (2) Source current (3) Compensating current

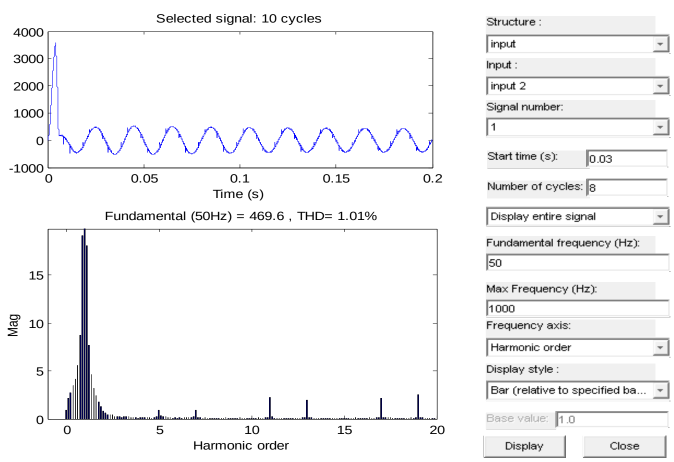

Fig. 7: SRF Theory, Butterworth type filter: (1) Source current for 10 cycles (2) FFT analysis

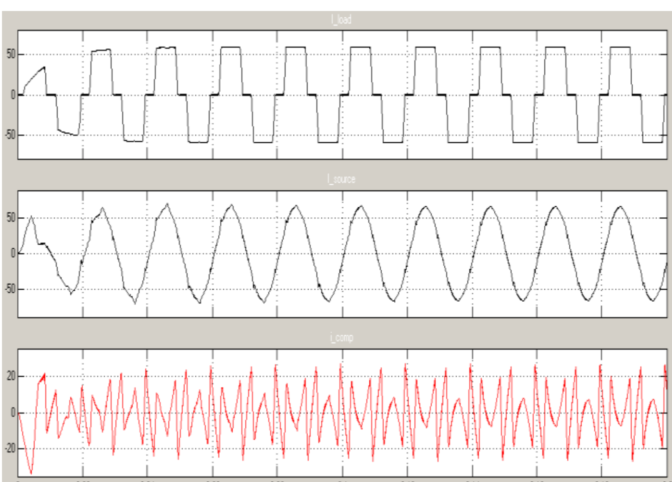

Fig. 8: Performance of SRF theory: (1) Load current (2) Source current (3) compensating current

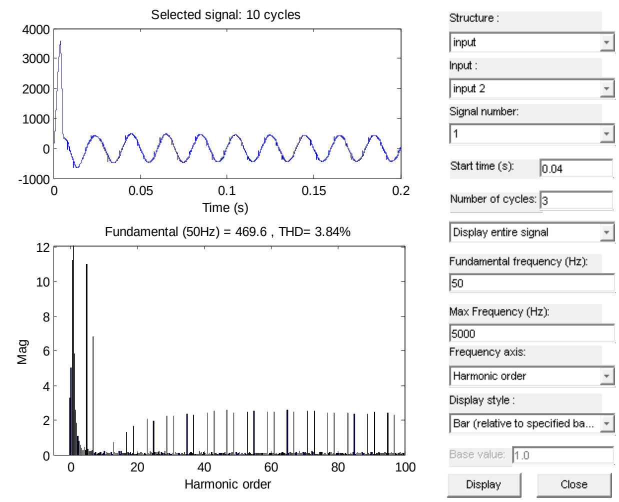

Fig. 9: SRF Theory, Chebyshev type filter: (1) Source current for 10 cycles (2) FFT analysis

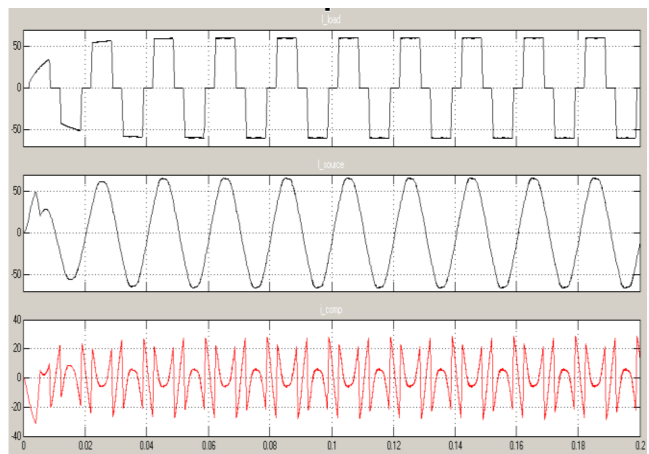

Fig. 10: Performance of id-iq theory: (1) Load current (2) Source current (3) Compensating current

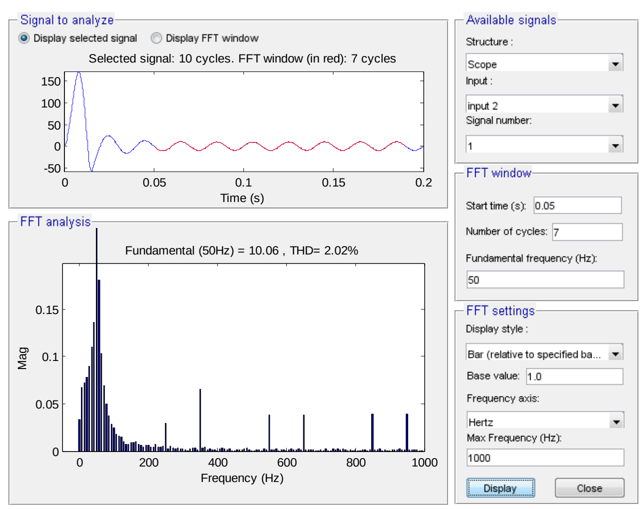

Fig. 11: id-iq Theory Butterworth type filter: (1) Source current for 5 cycles (2) FFT analysis

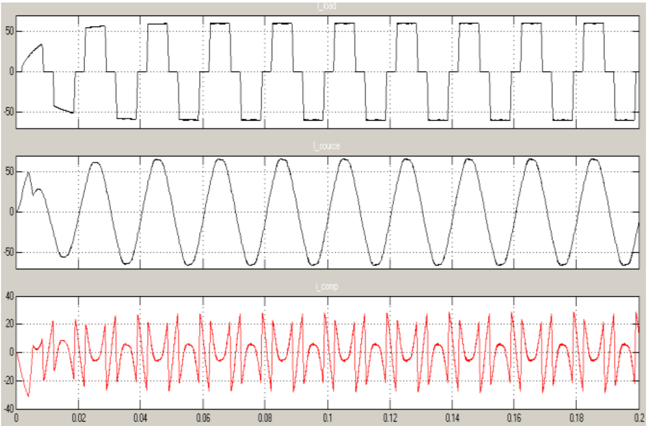

Fig. 12: Performance of id-iq theory: (1) Load current (2) Source current (3) Compensating current

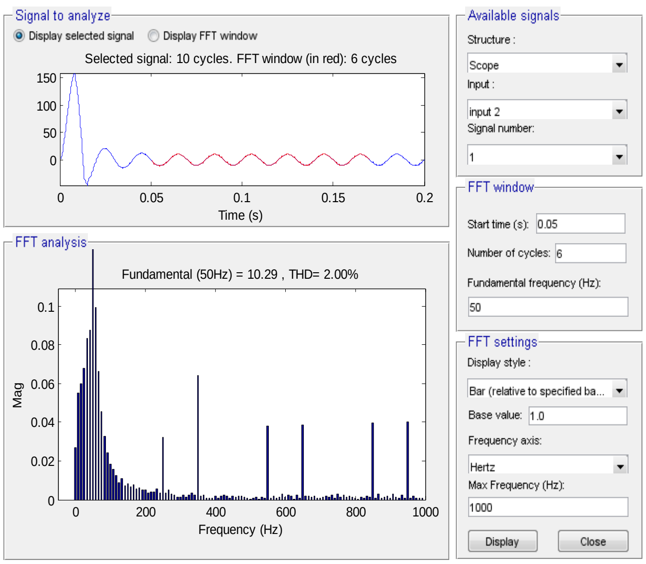

Fig. 13: i_d-i_q Theory Chebyshev type filter: (1) Source current for 6 cycles (2) FFT analysis

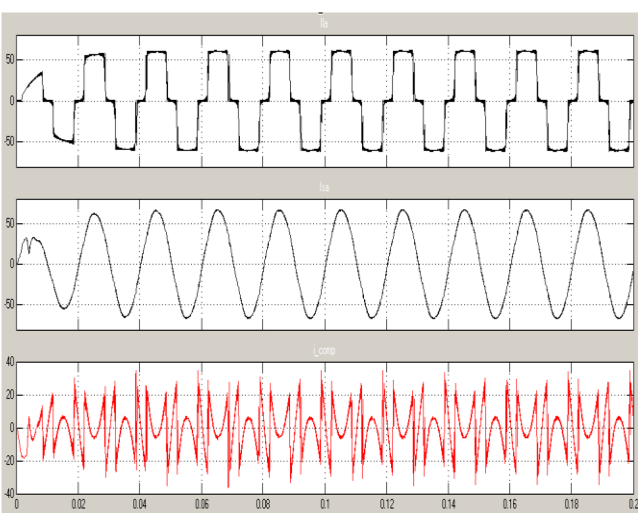

Fig. 14: Performance of Modified i_d-i_q theory: (1) Load current (2) Source current (3) compensating current

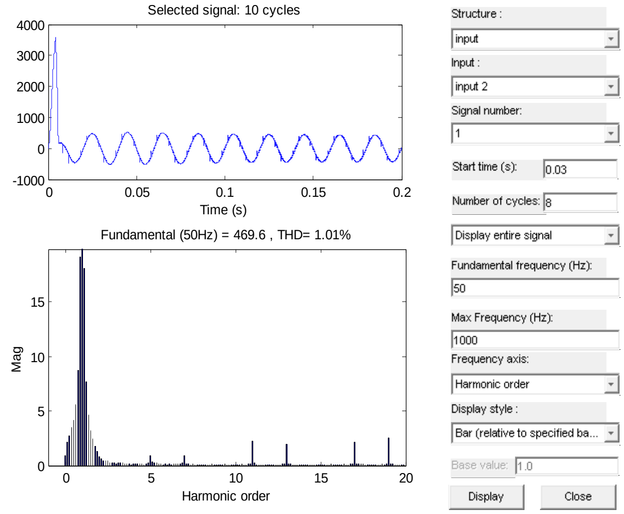

Fig.15: Modified i_d-i_q Theory Butterworth type filter: (1) Source current for 10 cycles (2) FFT analysis

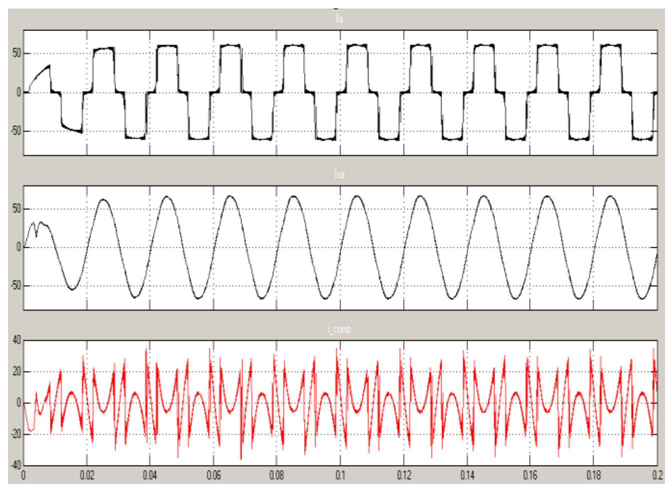

Fig. 16: Performance of Modified i_d-i_q theory: (1) Load current (2) Source current (3) compensating current

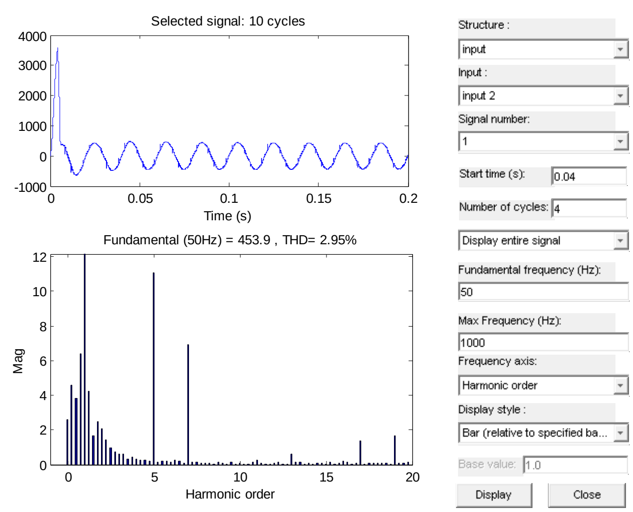

Fig. 17: Modified i_d-i_q Theory Chebyshev type filter: (1) Source current for 10 cycles (2) FFT analysis

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In real filtering, a Butterworth type filter is normally chosen, but chebyshev filter is also equally compatible for preparing experimental prototype. This particular filter type was chosen, in order to obtain magnitude and phase characteristics as close as possible to an ideal filter since its magnitude response is maximally flat in the passband and is monotonic in both passband and stopbands. To minimize the influence of the HPF's phase responses, an alternative HPF (AHPF) can also be used by mean of a low-pass filter (LPF) of the same order and cutoff frequency, simply by the difference between the input signal and the filtered one, which is equivalent in performance.

TABLE 1
Comparison of the Different SRF Methods

parameters	SRF Theory		Id-Iq Theory		Modified SRF Theory	
Filter type	BW	CH	BW	CH	BW	CH
Source Current THD(%)	1.01	3.84	2.02	2.00	1.01	2.95
5^{th} Harmonic	2.46	1.6	1.7	1.89	2.51	2.44
7^{th} Harmonic	1.52	1.4	1.15	1.23	1.57	1.52
9^{th} Harmonic	0.03	0.02	0.28	0.30	0.01	0.02
Load Perturbation Response	30 ms	40 ms	20 ms	25 ms	10 ms	10 ms
Requirement Of Ripple Filter	no	yes	yes	no	yes	no

BW = Butterworth, CH = Cheybshev (Type of Filter Used)

IV. CONCLUSION

This paper presents the compensation performance of all the different SRF techniques under sinusoidal voltage source condition as shown in table-1. Results are similar with gained source THD under IEEE 519, but under various filter type the chebyshev type filter is having superior performance compare to Butterworth filter for all methods. The Synchronous Reference Frame method is one of the most common and performing methods for detection of harmonics in active filters. An Improved Synchronous Reference Frame Method for the control of active power filters was presented. It is called Filtered Modified Reference Frame Method (FMRF) and is based on the same principle as the Synchronous Reference Frame method. However, this new method explores the fact that the performance of the active filter to isolate harmonics depends on the speed of the system that determines the rotating reference frame, but doesn't depend on its position. So, the delay introduced by the ac voltage filters, used for the detection of the reference frame, has no influence on the detection capability of the method. Compared with other methods, this new method presents some advantages due to its simplicity and its rudeness to perturbations on the ac network.

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