Three Phase Active Conditioner for Harmonics Mitigation

P.M. Balasubramaniam and G. Gurusamy

Abstract--- *The Shunt Active Power Filter is a very essential tool to remove harmonic currents and to reimburse reactive power for nonlinear loads. The fundamental standard of process of a Shunt Active Power Filter is to introduce an appropriate non-sinusoidal current (compensating current) into the system at the point of common coupling. This research work focuses on the time-domain approach for three-phase Shunt Active Power Filters through an effective algorithm. A fundamental outline and evaluation of the performance of existing improved algorithms for active power filters are presented. An enhanced approach based on time domain technique is proposed based on various complicated power quality problems and various compensation functions. It is observed that the proposed algorithm provides has shorter response time delay when compared with the conventional approaches. Therefore, the proposed approach can accurately attain various compensating current references.*

Index Terms--- *Shunt Active Power Filter, Synchronous Reference Frame, Instantaneous Reactive Power Theory, Point of Common Coupling*

I. INTRODUCTION

ELECTRIC power generated by the apparatus is distributed to the consumer in the form of 50 Hz ac voltage. The apparatus have a fixed control on the design and function of the apparatus used for transmission and distribution, and can thus keep frequency and voltage delivered to their consumers within close limits. However, increasing segments of loads connected to the power system consists of power electronic converters [1,2]. These loads are nonlinear and introduce distorted currents in the network which in turn produce harmonic voltage waveforms. With the proliferation of nonlinear loads such as diode/thyristor rectifiers, non-Sinusoidal currents degrade power quality in power Transmission/distribution systems [3]. Notably, voltage harmonics in power systems are becoming a serious problem for both utilities and customers. The deformation which may be due to a large single source or by the collective consequence of numerous small loads, often propagates for miles along distribution feeders [4, 5, 6]. As the application of non-linear power equipment is spreading, the power quality in the utility networks is greatly affected and it becomes a major issue. Thus, minimizing the voltage distortion has become an essential factor for both utilities and consumers.

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Figure 1 illustrates the block diagram of the distortion problem due to harmonic at low and medium power levels. Here, the utility is denoted by a perfect ac voltage source in series with lumped impedance representing lines and transformers. The voltage waveform at the point of common coupling is deformed due to harmonic current produced by the non-linear load.

This results in the following effects on the power system components

- Failure of harmonic sensitive loads
- Increased losses in parallel connected capacitor, transformers and motors
- Inappropriate functioning of protection relays and circuit breakers [7]

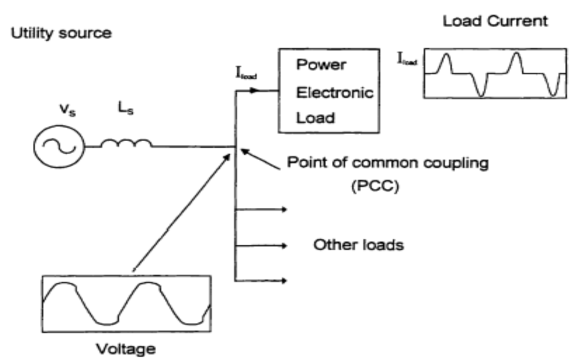

Figure 1: Harmonic Distortion at PCC

1.1 Distortions in Power ET Works

The different sources of distortion in power networks conveniently can be partitioned into three classes based on the power level of the equipment and frequency range as

- Sub-cycle distortion give rise to flicker and occur usually at the highest power level, they are caused by dynamic loads, such as arc furnaces, mill drives and mine winders.
- High frequency distortion is caused by modern power electronic apparatus, due to high rate of rise of current and voltage.
- Intra- cycle distortion, which covers a very wide range of power, and results from the power processing

technique. The distortion produced by these sources is generally termed “harmonics”.

1.2 Power in Distorted Ac Networks

The active and reactive power constituents for electric circuits with sinusoidal and linear loads are well recognized. The application of the reactive and the harmonic power is an actual requirement for achieving reactive power compensation and/or harmonic filtering in the scenario of non-linear loads. The component of the electric power is assuming a sinusoidal voltage supply and a non-linear load. In this scenario, the power factor is the product of the distortion factor by displacement factor [8].

Power Factor = Distortion factor x Displacement Factor

The displacement factor corresponds to the power factor of systems without harmonics. This factor may be called basic power factor, as it is based only on the current fundamental component. Alternatively, the power factor, may be called total power factor, as it is based on fundamental and all harmonic components.

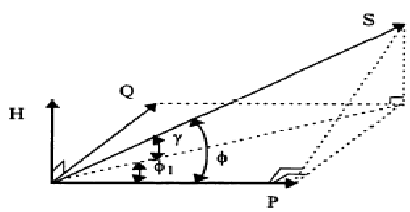

Figure 2: Power Tetragonal

Therefore, harmonics cause Lower power factor. The power components in distorted networks are denoted in power tetrahedron as shown in figure 2.

II. Active Filtering Technology

The primary effort to minimize harmonics without the utilization of traditional passive filters was made by B. Bird et al., [9].

This design depends on varying the waveform of the current drawn by the load by inserting a third harmonic current, displaced in phase, into the converter itself. But, it is not possible to fully eliminate more than one harmonic with this approach [10].

Ametani [11] presented another approach which is based on expanding the current injection technique to eliminate multiple harmonics. Based on this approach, an active control circuit could be utilized to accurately figure out the injected current. This current would comprise of harmonic segments of opposing phase, thus the harmonics would be neutralized, and only the basic component would remain [12]. Besides, the potential concept, Ametani was failed in creating a practical circuit competent of generating a precise current. The entire harmonic distortion was minimized, but single harmonics were not completely removed.

Alternatively, Sasaki and Machida [13] theorized that harmonics could be removed through principle of magnetic flux compensation. This in principle is the application of current to generate a flux to counteract the flux formed by the harmonics. Once again, theoretically, any number of harmonics could be removed directly. The current that would be needed to remove waveform deformation caused by harmonics was computed; however, a practical control circuit was not realized.

Recently, incredible development in capacity and switching performance of devices such as Bipolar Junction Transistors (BJT), Gate Turn-Off thyristors (GTO) and Insulated Gate Bipolar Transistors (IGBT), has spurred in the investigation of active power filters for harmonic compensation. Moreover, developments in topologies and control approaches for static PWM converters have enabled active power.

Filter using these converters to produce particular harmonic currents, such as produced by non-linear loads.

Since active power filters are potential tools for the compensation of current harmonics generated through distorting loads and also of reactive power, unbalance of nonlinear and fluctuating loads. They can be lesser, more adaptable, better damped, more choosy, and less susceptible to failure for component drift than its passive counterpart.

III. Active Filtering Approaches

3.1 Shunt Active Filters

The shunt active filter technique is based on the principle of injection of harmonic currents into the ac system, of the same amplitude but opposite in phase to that of the load harmonic currents. Figure 3 shows the active power filter compensation principle, which is managed in a closed loop approach to actively figure out the source current into sinusoid.

3.2 Series Active Filters

In series active filter configuration, a voltage source, is generated in such a way that when its voltage is added to the load voltage, the distorted voltage is removed, therefore resulting in a sinusoidal voltage at the Point of Common Coupling (PCC).

For harmonic compensation, both shunt and series active filters have lesser ratings than the obvious power of the load. The shunt active filter is rated for supply voltage, but a reduced current. In the case of series dynamic filters, the rated load current passes via the filter but the rated voltage is again lower. Hence, harmonic minimization can be implemented with converters having a minimized power rating.

3.3 Hybrid Active Filters

Hybrid structures were introduced for harmonic compensation of enormous rated loads in high voltage networks. Hybrid active filters configurations, integrates passive and active filters. These filters enhance the compensation features of the passive filters and hence realize a minimization in the rating of the active filter. They are specifically appropriate in installations where L-C tuned passive filters already exist.

In the hybrid series configuration, the series voltage injection is to be considered as an isolator, either attaining the harmonic currents to be supplied to the non-linear load or the harmonic currents that will be absorbed by the tuned LC-filters., series and shunt. In the initial scenario, the injected voltage is in series, and in the second scenario it is in series with the shunt passive filter.

IV. Control Methodology

Compensation of harmonies can be achieved in time-domain or frequency domain. The first approach depends on "on line" calculation of an instantaneous error function, at the same time the second approach exploits the principle of Fourier analysis and periodicity of the indistinct waveform to be corrected.

In time-domain, the error-function could be calculated in the following manner:

1. Extraction of the elementary constituent from the distorted waveform by using a notch filter.
2. Instantaneous reactive power compensation, which exploits an instantaneous orthogonal power transformation on mutually the actual and the fundamental constituents of voltage and current to generate a power function. The variation between these two transformations is the error.
3. Synchronous reference frame technique. Several PWM approaches exist (for compensation in the time-domain) to produce the gating signals to the switches and by this means to rebuild the distorted current.

The shunt APFs are exploited most extensively for stopping the current distortion. The performance of SAPF completely based on the characteristics of the enhanced approaches and controllers. On the other hand, typically one approach is only more suitable to some circumstances but not to all circumstances. An improved algorithm of SAPF for harmonic elimination, power factor correction, and balancing of nonlinear loads is proposed in this paper.

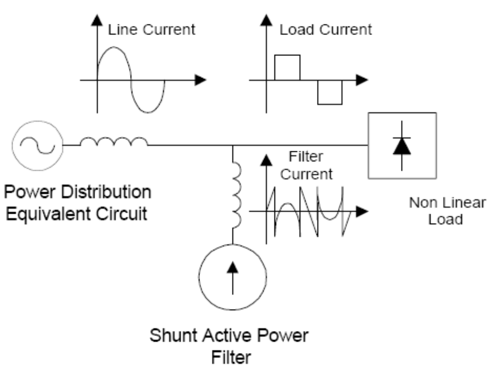

Figure 3: SAPF System

4.1 Simulink Model of the Overall System

The simulation of power electronic systems offers more benefits in the design process by permitting several alternatives. In order to confirm the practicability of the proposed approach, a virtual implementation of the SAPF is made using Simulink. The major elements are the reference compensation current detector, a phase loop lock, a current controller, and a DC voltage controller. The reference compensation currents are concluded and are provided as input to a current controller to generate signals of the PWM inverter. Additionally, since the capacitor voltage at the inverter terminal must be preserved at a stable level, the loss generated by switching and capacitor voltage deviation is provided by the source. Simulations reveal that the compensation current calculator yields minor time delay in steady state for the SAPF operation

4.2 Mathematical Modeling of the Proposed Method

In the three-phase three-wire arrangement, the instantaneous load currents of phase "a," "b," "c" (i_a,i_b, and i_c) can be disassembled into positive-sequence and negative-sequence constituents based on the symmetrical weigh law, which was developed by Fortes cue independently.

$$i_x(n)=\sum_{k=1}^{\infty}\left[I_{1k}Sin\left(\frac{2\pi nk}{N}+\phi_{1k}-\frac{2l\pi}{3}\right)+I_{2k}Sin\left(\frac{2\pi nk}{N}+\phi_{2k}+\frac{2l\pi}{3}\right)\right] \quad (1)$$

Where,

$$l=\begin{cases}0 & x=a\\1 & x=b\\2 & x=c\end{cases}$$

Normally, only the positive-sequence, negative-sequence, active power and reactive power of the elementary current are concerned, and it is not essential to decompose the harmonic. Subsequently, the essential current component is given as follows

$$\begin{aligned}i_{x1}(n) &= I_{11}Sin\left(\frac{2\pi}{N}n+\phi_{11}-\frac{2l\pi}{3}\right)+I_{21}Sin\left(\frac{2\pi}{N}n+\phi_{21}+\frac{2l\pi}{3}\right)\\ &= I_{11}Sin\left(\frac{2\pi}{N}n-\frac{2l\pi}{3}\right)Cos\phi_{11}\\ &+I_{11}Cos\left(\frac{2\pi}{N}n-\frac{2l\pi}{3}\right)Sin\phi_{11}\\ &+I_{21}Sin\left(\frac{2\pi}{N}n-\frac{2l\pi}{3}\right)Cos\left(\phi_{21}-\frac{2l\pi}{3}\right)\\ &+I_{21}Cos\left(\frac{2\pi}{N}n-\frac{2l\pi}{3}\right)Sin\left(\phi_{21}-\frac{2l\pi}{3}\right)\end{aligned} \quad (2)$$

The initial term of (2) represents the positive-sequence component in phase with the phase voltage, which is the active power constituent of the positive- sequence elementary current; the second term of (2) represents the positive-sequence element orthogonal with the line voltage, which is the reactive power constituent of the positive-sequence elementary current; the third term of (2) represents the negative-sequence element in phase with the line voltage, which is the active power component of the negative-sequence elementary current; the forth term of (2) represents the negative-sequence component orthogonal with the line voltage, which is the reactive power element of the negative sequence elementary current.

Fig. 4 illustrates the block diagram of the proposed current-detection approach, in which '$Sin\frac{2\pi}{N}n$' is synchronous with the positive-sequence elementary voltage of phase "a," which decides the calculation precision of active and reactive power constituents. The low-pass filter which is utilized decides the performance of the complete system. In accordance with different compensation purposes, the segregator will acquire different elements appropriately, which is advanced to the algorithm depending on the instantaneous reactive power theory.

V. Gain Selection

In accordance with the above configuration, the control difficulty trims down to select the accurate gains for the model of Fig. 4.4 for a variety of operating conditions. Considering the sampling delay, the plant is an uncomplicated lag along with an integrating component

$$H_{plant} = \left(\frac{1}{1+sT_s}\right)\left(\frac{U}{s}\right) \tag{3}$$

Where T represents the sampling time. The open-loop transfer function H_{01} with the controller then becomes

$$H_{o1} = \left(K_{pll}\frac{1+sT_{pll}}{sT_{pll}}\right)\left(\frac{1}{1+sT_s}\right)\left(\frac{U}{s}\right) \tag{4}$$

Where K_{pll}, T_{pll} indicates the gains related with the PI regulator. This is a typical control setback very comparable to a current controlled speed loop of a drive system in which the integral term in the plant imitates the mechanical inertia and the lag element emulates the current control loop. Numerous techniques can be exploited to choose the gains depending on the preferred performance condition.

In this paper, the technique of symmetrical optimum was exploited to compute the regulator gains. Based on this technique, the regulator gains K_{pll} and T_{pll} are chosen such that the amplitude and the phase plot of H_{01} are symmetrical regarding the crossover frequency ω_c, which is at the geometric mean of the two corner frequencies of H_{0l}. A normalizing factor α is specified, the frequency ω_c, K_{pll}, T_{pll} are connected as following equation,

$$\left.\begin{aligned} \omega_c &= 1/(\alpha T_s) \\ T_{pll} &= \alpha^2 T_s \\ K_{pll} &= (1/\alpha)(1/(UT_s)) \end{aligned}\right\} \tag{5}$$

Replacing (4) into (5) it can be revealed that the factor α and the damping factor ξ are connected by the association

$$\xi = \frac{\alpha - 1}{2}$$

By altering α, the system bandwidth and damping can be managed.

A three-phase PLL system was formulated which is appropriate for time domain investigation under indistinct utility conditions and it was tuned the control effects, for instance, loss of gain, line harmonics and frequency disturbances. The PLL was entirely executed in software without the utilization of any hardware filters. When the reference u_{de}^* is fixed to zero, the θ^* computed is synchronous with the positive-sequence constituent of elementary voltage. When u_{de}^* is not fixed to zero, a constant phase difference is between the θ^* and the positive-sequence constituent of elementary voltage, which make the control of the displacement feature easy. In addition, this phase difference will not influence the strength of the chosen harmonics detection. The resultant simulation diagram of the SPLL is shown in Fig.5.

The phase voltage is determined by per-unit; the base quantities for per-unit value are the maximum value of positive-sequence elementary phase voltage. Subsequently, three phase voltages can be determined as, $Sin\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right)$ correspondingly. The instantaneous power of the elementary current can be acquired by multiplying current by phase voltage as follows

$$\begin{aligned} & i_{x1}(n) * Sin\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right) \\ &= \frac{1}{2}\left\{ I_{11}Cos\phi_{11}\left[1 - Cos\left(\frac{4\pi}{N}n - \frac{4l\pi}{3}\right)\right]\right. \\ &+ I_{11}Sin\phi_{11}Sin\left(\frac{4\pi}{N}n - \frac{4l\pi}{3}\right) \\ - \quad &+ I_{21}Cos\left(\phi_{21} - \frac{2l\pi}{3}\right)\left[1 - Cos\left(\frac{4\pi}{N}n - \frac{4l\pi}{3}\right)\right] \\ & \left. I_{21}Sin\left(\phi_{21} - \frac{2l\pi}{3}\right)\mathrm{Sin}\left(\frac{4\Pi}{N}n - \frac{4l\pi}{3}\right)\right\} \end{aligned} \tag{6}$$

The initial term of the equation represents the instantaneous active power element of the positive-sequence elementary (the sum of three phases is steady, which adds to the overall power delivered from source to load). The second term of the equation represents the instantaneous reactive power element of the positive-sequence elementary (the total of three phases is zero, which travels between the phases and can be balanced by a compensator without an energy storage component). The third term represents the instantaneous active power element of the negative-sequence elementary (the three-phase total of the previous portion of this item is zero, which travels between the phases and can also be balanced by a compensator without an energy-storage component). The three-phase sum of the remaining (together with the posterior part of the third and fourth terms, which is equal to $-I_{21}Cos\left(\frac{4\pi}{N}n - \varphi_{21}\right)$ and equivalent for each phase) is not zero, and its frequency is two times the elementary, which can be balanced by a compensator with an energy-storage element). As a result, the negative-sequence elementary currents do not add to the power delivered to the load. In the same way, the instantaneous power of harmonics can be obtained by multiplying current as follows

$$i_{xk}(n)$$
$$= \frac{1}{2}\left\{ I_{1k}\left[Cos\left(\frac{2n\pi}{N}(k-1)+\phi_{1k}\right) - Cos\left(\frac{2n\pi}{N}(k+1)+\phi_{1k}+\frac{2l\pi}{3}\right)\right] + I_{2k}\left[Cos\left(\frac{2n\pi}{N}(k-1)+\phi_{2k}-\frac{2l\pi}{3}\right) - Cos\left(\frac{2n\pi}{N}(k+1)+\phi_{2k}\right)\right]\right\} \quad (7)$$

It can be seen that either the negative-sequence or positive-sequence constituent has one portion of which the three-phase sum equal to zero, which can be balanced by a compensator without energy storage, and the remaining can be balanced by a compensator with energy storage.

In (7) and (8), the least frequency constituent is two times the elementary frequency; the dc constituent can be obtained by a low-pass filter with a cutoff frequency lesser than double the elementary frequency or by a sliding-window with N/2 samples. Subsequently, multiplying by 2, the following equation can be obtained:

$$B_{x1} = I_{11}Cos\phi_{11} + I_{21}Cos(\phi_{21} + 4l\pi/3) \quad (8)$$

$Cos\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right)$

Multiply (1) with the following equation

$$i_x(n) * Cos\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right) =$$
$$\frac{1}{2}\left\{ I_{11}\left[Sin\phi_{11} + Sin\left(\frac{4\pi}{N}n + \phi_{11} - \frac{4l\pi}{3}\right)\right] + I_{21}\left[Sin\left(\frac{4\pi}{N}n + \phi_{21}\right) + Sin\left(\phi_{21} + \frac{4l\pi}{3}\right)\right] + i_h\right\} \quad (9)$$

can be obtained. Using the similar technique, the following equations can also be obtained

$$A_{x1} = I_{11}Sin\varphi_{11} + I_{21}Sin(\varphi_{21} + 4l\pi/3) \quad (10)$$

Here, define

$$\begin{pmatrix} A_{11} & B_{11} \\ A_{21} & B_{21} \end{pmatrix} = \begin{pmatrix} I_{11}Sin\varphi_{11} & I_{11}Cos\varphi_{11} \\ I_{21}Sin\varphi_{21} & I_{21}Cos\varphi_{21} \end{pmatrix} \quad (11)$$

In (11) A_{11} and B_{11} represents the peak values of the reactive power constituent and active power constituent of positive-sequence elementary current, correspondingly. A_{21} and B_{21} are the maximum values of the reactive power constituent and active power constituent of negative-sequence elementary current of phase "a," correspondingly. In accordance with phase "b" and "c," the maximum values are

$I_{21}Sin(\varphi_{21} - 2\pi/3)$, $I_{21}Cos(\varphi_{21} - 2\pi/3)$ and $I_{21}Sin(\varphi_{21} + 2\pi/3)$, $I_{21}Cos(\varphi_{21} + 2\pi/3)$, respectively, in the same way, multiplying

$2Sink\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right)$ and $2Cosk\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right)$, correspondingly, and going through the low-pass filter, A_{xk} and B_{xk} can be obtained:

$$A_{xk} = I_{1k}Sin\left[\frac{2(k-1)l\pi}{3} + \varphi_{1k}\right] + I_{2k}Sin\left[\frac{2(k+1)l\pi}{3} + \varphi_{21}\right] \quad (12)$$

$$B_{xk} = I_{1k}Cos\left[\frac{2(k-1)l\pi}{3} + \varphi_{1k}\right] + I_{2k}Cos\left[\frac{2(k+1)l\pi}{3} + \varphi_{21}\right] \quad (13)$$

$Sin\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right)$

Subsequently, define

$$i_{x11} = A_{11}Cos\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right) + B_{11}Sin\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right) \quad (14)$$

$$i_{x21} = A_{21}Cos\left(\frac{2\pi}{N}n + \frac{2l\pi}{3}\right) + B_{21}Sin\left(\frac{2\pi}{N}n + \frac{2l\pi}{3}\right) \quad (15)$$

$$i_{x1} = A_{x1}Cos\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right) + B_{x1}Sin\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right) \quad (16)$$

$$i_{xk} = A_{x1}Cos\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right) + B_{xk}Sink\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right) \quad (17)$$

Equations (11)–(16) generate the segregator shown in Fig. 4, by which numerous results can be accomplished based on different compensation purpose. When the SAPF is exploited to balance harmonics and the negative-sequence constituent of the elementary current, the positive-sequence constituent of the elementary current i_{x11} can be obtained from (14), and the current reference can be acquired as $i^*_{cx}(n) = i^*_x(n) - i_{x11}(n)$ by subtracting i_{x11} from the load current. When the line current after balancing is anticipated to be a symmetrical three-phase elementary current, and the power factor is 1, the active power constituent of the positive-sequence elementary current i_{px11} can be acquired by considering $A_{11} = 0$ in (4.14), and the current reference can be acquired as $i^*_{cx}(n) = i_x(n) - i_{px11}(n)$ by subtracting i_{px11} from the load current. In the same way, by fixing B_{11} to zero, the reactive power constituent of the positive-sequence elementary current can be acquired. The negative-sequence constituent of the elementary current can be acquired by (15). When the APF is employed to balance the chosen order harmonics, the compensating reference can be acquired by (17). In fact, the "active power" constituent and "reactive power" constituent of harmonics do not require to be segmented, as a result the factors $Cosk\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right)$ and $Sink\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right)$ can be substituted with $Sin\left(\frac{2nk\pi}{N}\right)$ and $Cos\left(\frac{2nk\pi}{N}\right)$ separately. Subsequently, the programming can be significantly simplified. In accordance with the detection techniques, several compensation aims can be accomplished by using specific combinations.

VI. Simulink Model of the Improved Algorithm

The major elements of the current detection approach comprise a Soft Phase Loop Lock, a sine wave generator and the separator. The current detection approach is employed based on the proposed approach to decide the reference balancing current. Fig. 4.6 and 4.7 illustrates the Simulink model of the current detection approach and the Soft Phase Loop Lock correspondingly.

It is clear from the above investigation that the delay resultant from the proposed approach is almost less than half of the main cycle, which is half of that of DFT and the equivalent as that of the approach depends on IRPT. In addition, the algorithm proposed

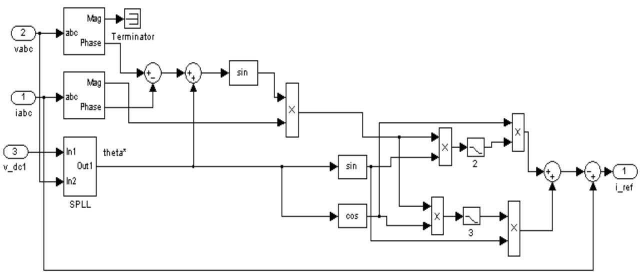

Figure 4: Simulation Diagram of the Proposed Improved Algorithm

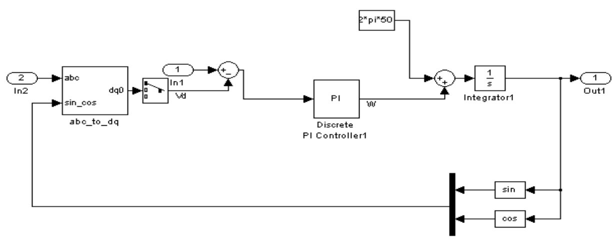

Figure 5: Simulation Diagram of the Phase Locked Loop

Possibly will sense the positive/negative-sequence elementary current, active/reactive power constituent of positive-sequence elementary current and selective harmonics appropriately, which is more flexible than the algorithm depending on IRPT and DFT.

VII. Simulation Conditions

The major intention of the simulation is to reveal the effectiveness of the proposed SAPF control approach. Two test cases are considered with variety of source voltages and load conditions. In case 1, the source voltages are sinusoidal and balanced with a magnitude of 230 V and a frequency of ω=100π and the source supplies an imbalanced nonlinear load. In case 2, imbalanced / distorted source voltages provide an imbalanced nonlinear load in parallel with an imbalanced load.

7.1 Simulation Results for Sinusoidal, Balanced Source Voltages

The balanced and sinusoidal three phase voltages taken into consideration are, V_a =230 sin (ωt)

$$V_b=230 \sin (\omega t-120^o)$$

$$V_c=250 \sin (\omega t+120^o)$$

The load exploited is a bridge rectifier which operates as a nonlinear imbalanced load .The simulation results have been plotted individually for a comprehensible investigation.

Figure 6, Figure 7, Figure 8, illustrates the source voltage, line current, reference compensation current and source current after compensation for the three phases correspondingly.

Figure 6 illustrates the source voltage, load current and the source current after compensation. Simulation results of compensation current produced by the controller are revealed in Figure. 7.

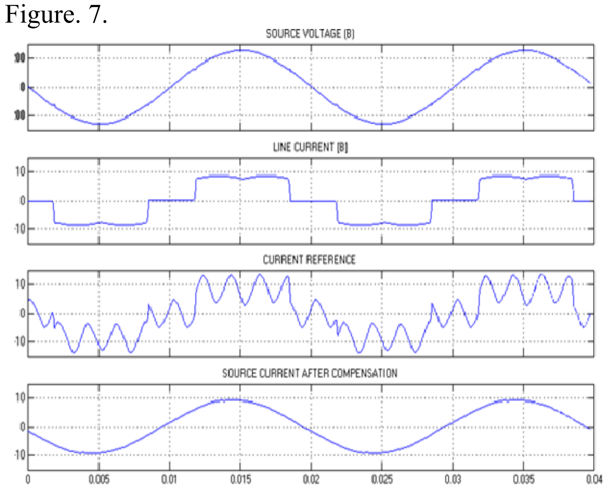

Figure 6: Source Voltage, Line Current, Current Reference and Source Current after Compensation for Phase A

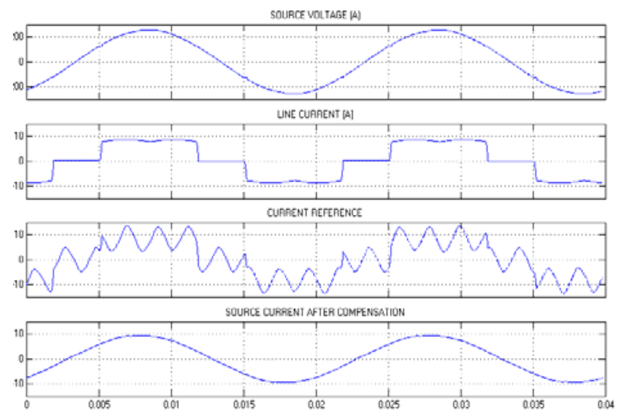

Figure 7: Source Voltage, Line Current, Current Reference and Source Current after Compensation for Phase B

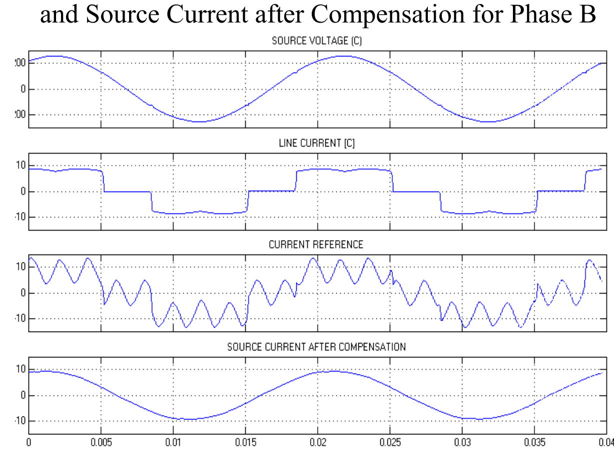

Figure 8: Source Voltage, Line Current, Current Reference and Source Current after Compensation for Phase c

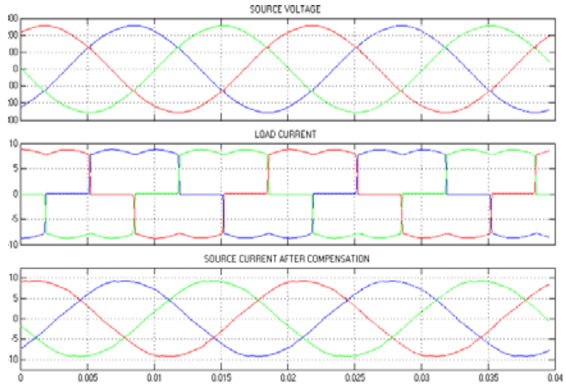

Figure 9: Source Voltage, Load Current and Source Current after Compensation

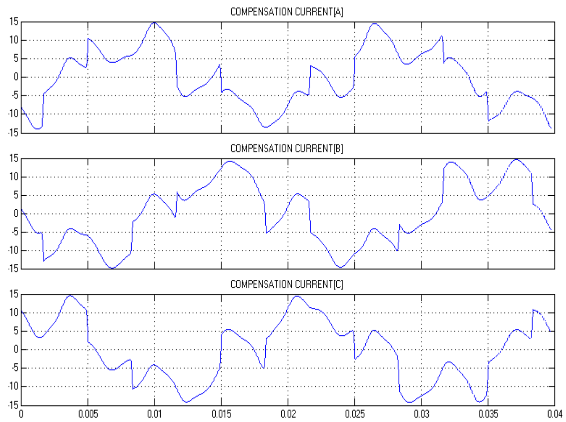

Figure 10: Compensation Currents

7.2 Simulation Results for Unbalanced / Distorted Source Voltages

In this case, 230 V, 50Hz three phase voltage source is taken into consideration and 3rd order harmonic of 0.2 amplitude, phase angle zero is introduced in the positive sequence constituent of phase A and a

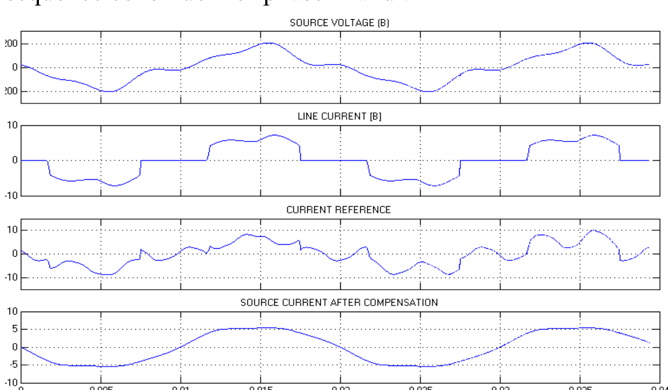

Figure 11: Source Voltage, Line Current, Current Reference and Source Current after Compensation for Phase A

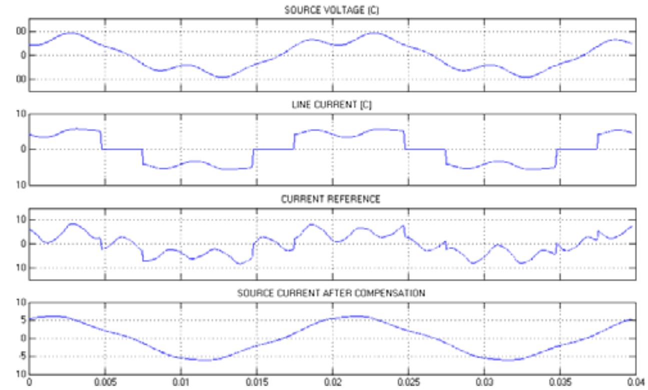

Figure 12: Source Voltage, Line Current, Current Reference and Source Current after Compensation for Phase B

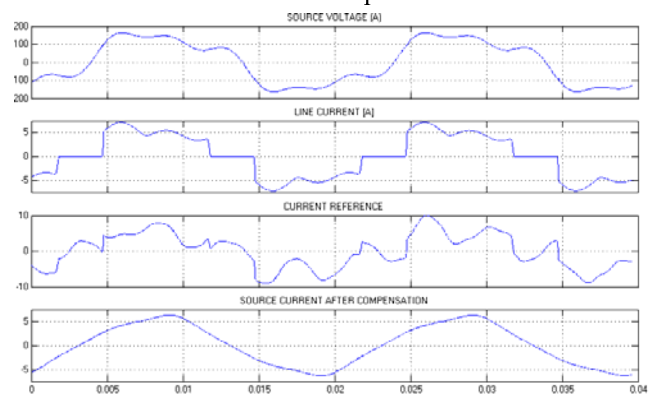

Figure 13: Source Voltage, Line Current, Current Reference and Source Current after Compensation for Phase C

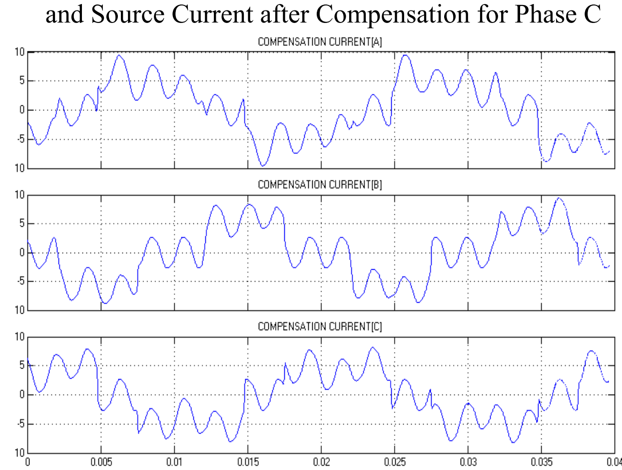

Figure 14: Compensation Currents

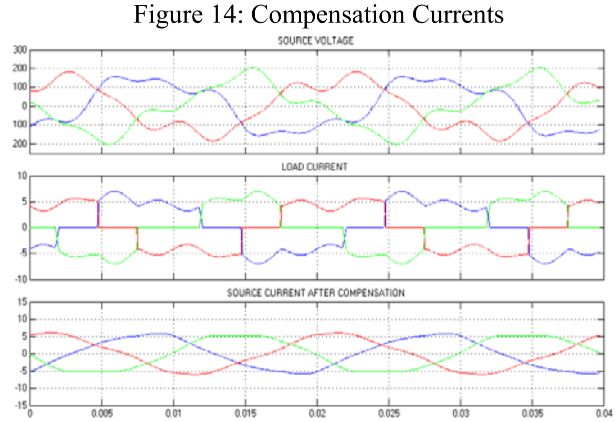

Figure 15: Source Voltage, Load Current and Source Current after Compensation

S.No	Method for reference compensation current calculation	% THD of source current for balanced supply voltage	% THD of source current for unbalanced supply voltage
1	GIRPT method	1.87	9.59
2	SRF method	3.60	9.42
3	SCD method	0.98	8.91
4	Proposed method	0.93	8.70

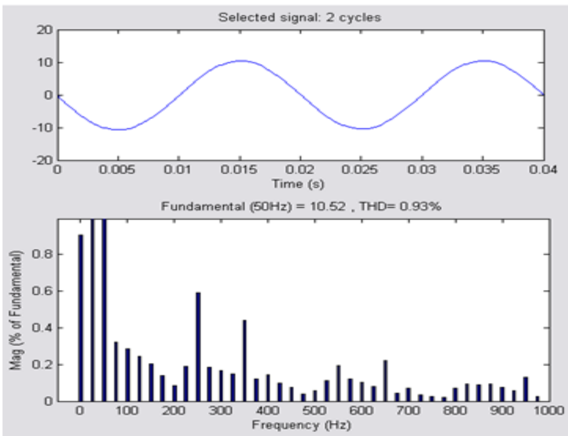

Figure 16: THD Plot for Balanced Case

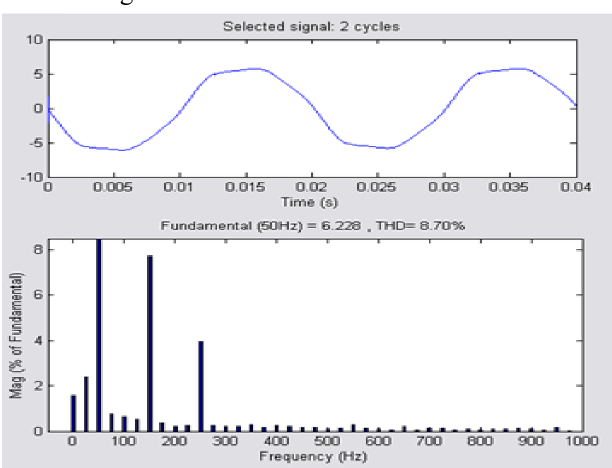

Figure 17: THD Plot for UN Balanced Case

Fifth order harmonic of magnitude 0.15, phase angle 35^o is introduced in the negative sequence constituent of phase B for a time period of 0 to 1 seconds.

Figure 11, Figure 12, Figure 13 illustrate the source voltage, line current, reference compensation current and source current after balancing for the three phases correspondingly.

Figure 12 illustrates the source voltage, load current and the source current after compensation. Simulation results of compensation current produced by the controller are illustrated in Figure 14.

VIII. Analysis of Simulation Results

The simulation results are available for two cases considered. It is clear that the SAPF injects harmonic currents into the line thereby making the input supply sinusoidal.

The comparison of THD is given in Table 1 for the three reviewed and available methods namely Generalized Instantaneous Reactive Power Theory based methods, Synchronous Reference Frame method and the Synchronous Current Detection methods. From the results (Figure. 16 and Figure 17) it observed that for both balanced and unbalanced source voltages the THD for the proposed method is less than the available methods and also the delay resulting from the proposed algorithm is less than half of the main cycle, which is half of that of DFT and the same as that of the algorithm based on IRPT.

Table 1: Comparison of % THD

IX. Conclusion

This research work has formulated the mathematical modeling and design of the reference compensation current controllers for shunt active power filters based on time domain approach. The simulation results of the proposed approach are compared with that of the available results of Generalized Instantaneous Reactive Power Theory based method, Synchronous Reference Frame method and the Synchronous Current Detection methods. From the results it can be concluded that the delay resulting from the proposed algorithm is less than half of the main cycle, which is half of that of DFT and the same as that of the algorithm based on IRPT. From the analysis and simulation it is found that the algorithm presented in this thesis has the advantages of flexibility, accuracy and easy implementation. Since the reference compensation currents are determined in the 'a-b-c' reference frame, there is no reference frame transformation is required. Therefore, it results in less complexity in realizing the control circuit of SAPF and still maintains good filter performance. After SAPF injects the compensation currents, it is found that the source currents become ideal and remain in phase with the positive-sequence fundamental source voltages. Therefore, the utility source power factor at the positive sequence fundamental frequency is achieved and the harmonic currents are well controlled. The Total Harmonic Distortion (THD) study reveals that the proposed method has a source current THD less than the available methods. The proposed compensation strategy of the SAPF is verified through MATLAB/Simulink which yields good agreement with the expected SAPF goals.

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