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Simulation Study and Comparative Analysis of Different Control Techniques used for Three Phase Three Wire Shunt Active Filters

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Abstract: *This paper describes the three different techniques used for the generation of real time reference current for shunt active filter in three phase three wire system. All three techniques are analyzed mathematically and simulation results are evaluated and compared in terms of compensation performance with multi parameter under steady state conditions. The first strategy is based on instantaneous active-reactive power theory proposed by. Akagi et al.,in 1983. The second one is based on instantaneous active-reactive current component theory. The third one is based on the power definitions proposed by Fryze in the last century also called current minimization method. Finally all three strategies are compared with their compensation performance with reference to the harmonics and reactive power. All above three methods are completely frequency independent. Simulation results are obtained under sinusoidal balanced voltage source condition assuming constant dc bus voltage of PWM inverter. The comparison and effectiveness of all the methods is based on the theoretical analysis and simulation results employing a three phase three wire test system supplying rectifier as a non-linear load.*

Keywords: *Reference Current, Shunt Active Filter, PQ Theory, Instantaneous Current Component Theory, Generalized Fryze Current Theory.*

1. INTRODUCTION

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 reference template must include the amplitude and phase information to produce the desired current component compensation, while keeping the voltage across the dc bus constant. The reference generation scheme must operate adequately under steady state and transient conditions [9, 10]. All the methods used to generate the reference signal require a low pass filter to extract the compensating components from the load current. The filtering process affects the dynamic response of the reference generation scheme under steady state or transient operating conditions. The compensation performance of the active filter is severely affected if the voltage supply is not ideal. It is important to note that either digital or analog circuitry implementation requires a low passive filter [14, 15].

The control strategy for a shunt active power filter (Figure 1) 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 dead-beat control. Sometimes, it is useful to calculate the compensating current in terms of the reference source current In this paper, four different generation techniques used to obtain current reference signal in active power filters compensating three-wire power distribution systems are compared. Each technique is analyzed and compared in terms of the operation under balanced and unbalanced load conditions. Cut-off frequency of the control low pass filter used to extract the compensation component of the load current, and the effect of unbalanced load condition is being checked. The basic principle of a shunt active power filter is shown in Figure 1.

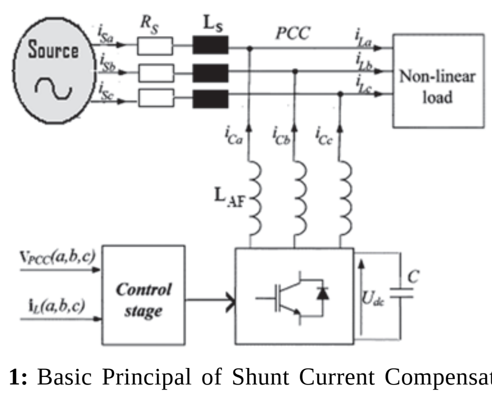

Figure 1: Basic Principal of Shunt Current Compensation for Three Phase System

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$$I_{Comp} = I_{Source} - I_{Load} \quad (1)$$

Where I_{Comp} is the compensation input current, I_{Source} is the source current and I_{Load} is the load current, respectively. The main feature of the active power filter is that the supply current is forced to be sinusoidal and in phase with the supply voltage regardless of the characteristics of the load. Therefore, the shunt APF is harmonics cancellation and reactive power compensation by injecting equal but opposite harmonic and reactive currents into the supply line by means of solid-state amplifier circuits.

2. INSTANTANEOUS REACTIVE POWER THEORY

In 1983 *Akagi et al.* [6-9] proposed a new theory for the control of active filters in three-phase power systems called "Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits", also known as "Theory of Instantaneous Real Power and Imaginary Power", or "Theory of Instantaneous Active Power and Reactive Power", or "Theory of Instantaneous Power", or simply as "p-q Theory". It is based on instantaneous values in three-phase power systems with or without neutral wire, and is valid for steady-state or transitory operations, as well as for generic voltage and current waveforms.

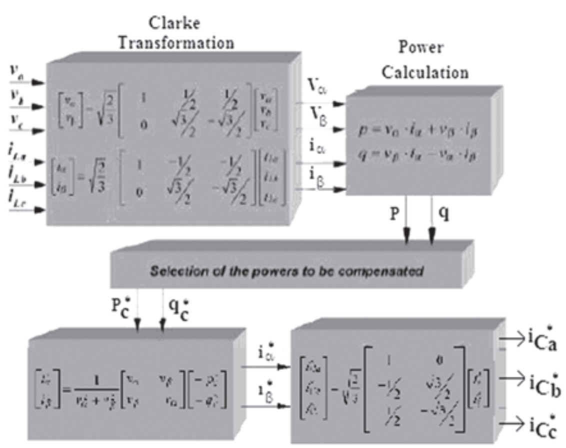

Figure 2: Control Method for Shunt Current Compensation based on *p-q* Theory

The theory is applicable to three-phase four-wire systems, as well as to three-phase three-wire systems. In addition, it is characterized by allowing us to define the instantaneous reactive power in each phase as a unique value for arbitrary three-phase voltage and current waveforms without any restriction, and by yielding a lucid explanation of the physical meaning of instantaneous reactive power. Another advantage of this theory is the simplicity of its calculations, since only algebraic operations are required. The only exception is in the separation of some power components in their mean and alternating values. However, as it will be shown in this paper, it is possible to exploit the symmetries of the instantaneous power waveform for each specific power system, achieving a calculation delay that can be as small as 1/6 and never greater than 1 cycle of the power system frequency. It is also shown that calculations for reactive power and zero-sequence compensation do not introduce any delay. The instantaneous power theory implements a transformation from a stationary reference system in *a-b-c* coordinates, to a system with coordinate's α-β-*0*. It corresponds to an algebraic transformation, known as *Clarke* transformation [7, 8], which also produces a stationary reference system, where coordinates α-β are orthogonal to each other, and coordinate *0* corresponds to the zero-sequence component. The zero sequence component calculated here differs from the one obtained by the symmetrical components transformation, or *Fortescue* transformation, by a 3 factor. These three phase coordinates can be transformed on to α–β coordinates as per Clarke transformation theory. C is Clarke transformation matrix.

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = C \begin{bmatrix} V_a \\ V_b \\ V_C \end{bmatrix} \qquad \begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} = C \begin{bmatrix} I_a \\ I_b \\ I_C \end{bmatrix} \quad (2)$$

$$C = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}$$

By conventional theory

$$P_{30} = V_a i_a + V_b i_b + V_c i_c = V_0 i_0 + V_\alpha i_\alpha + V_\beta i_\beta \quad (3)$$

$$\begin{bmatrix} P_0 \\ P \\ q \end{bmatrix} = \begin{bmatrix} V_0 & 0 & 0 \\ 0 & V_\alpha & V_\beta \\ 0 & -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} \quad (4)$$

For three phase three wire system $I_0 = 0$, so zero sequence power $P_0 = 0$, and consequently power equation will be

$$\begin{bmatrix} P \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \quad (5)$$

Using equations (5) and (6) the instantaneous active and reactive load powers can be obtained by following

$$\begin{bmatrix} P_l \\ q_l \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_{l\alpha} \\ I_{l\beta} \end{bmatrix} \quad (6)$$

Which can be decomposed into oscillatory and average terms as $p_l = \tilde{p}_l + \bar{p}_l$ and $q_l = \tilde{q}_l + \bar{q}_l$. Under balanced and sinusoidal mains voltage conditions the average power components are related to the first harmonic current of positive sequence $i_{l_1}^{+}$ and the oscillatory components represent all higher order current harmonics including the first harmonic current of negative sequence. Thus, the AF should compensate the oscillatory power components so that the average power components remain in the mains. The ac component of the real power in the α-β reference frame is obtained by using a 2nd order high pass filter with cut-off frequency of 100 Hz and damping constant $\delta = 0.7$.

$$\begin{bmatrix} iC_\alpha \\ iC_\beta \end{bmatrix} = \frac{1}{V_\alpha^z - V_\beta^z} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} p_c \\ q_c \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} I_{comp.a} \\ I_{comp.b} \\ I_{comp.c} \end{bmatrix} = [C]^T \begin{bmatrix} iC_\alpha \\ iC_\beta \end{bmatrix} \tag{8}$$

After eliminating the average power components by high-pass filters (HPF) the powers to be compensated are p_c and q_c. The compensation currents are obtained by inverting the matrix in (8). These current can be calculated by (9) and (10).

3. INSTANTANEOUS CURRENT COMPONENT THEORY

In this method the compensating currents are obtained from the instantaneous active and reactive current components and of the nonlinear load. In the same way, the mains voltages $V_{(a,b,c)}$ and the polluted currents $il_{(a,b,c)}$ in α-β components must be calculated as in the previous method by (2). However, the load current components are derived from a synchronous reference frame based on the Park transformation, where represents the instantaneous voltage vector angle (9).

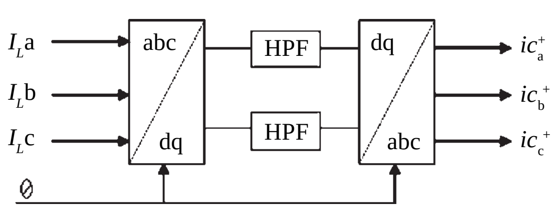

Figure 3: Principal of the Synchronous Reference Frame Method

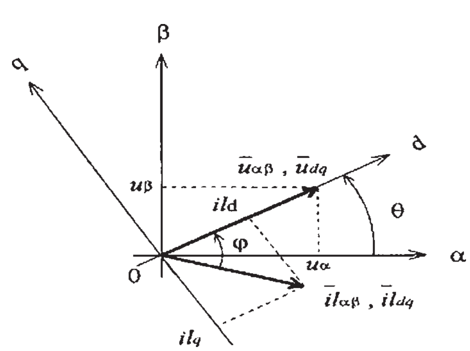

Figure 4: Voltage and Current Space Vectors in the Stationary and Synchronous Reference Frames.

$$\begin{bmatrix} il_d \\ il_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} il_\alpha \\ il_\beta \end{bmatrix} \tag{9}$$

Where, $\theta = \tan^{-1}\dfrac{V_\beta}{V_\alpha}$

Figure 4, depicts the voltage and current space vectors in the stationary (α-β) and rotating frames (d-q). Under balanced and sinusoidal mains voltage conditions angle θ is a uniformly increasing function of time. This transformation angle is sensitive to voltage harmonics and unbalance; therefore dè/dt may not be constant over a mains period. With transformation (9) the direct voltage component is $V_d = \sqrt{V_\alpha^2 + V_\beta^2}$ and the quadrature voltage component is always null, $V_q = 0$, so due to geometric relations (9) becomes

$$\begin{bmatrix} il_d \\ il_q \end{bmatrix} = \frac{1}{\sqrt{V_\alpha^2 - V_\beta^2}} \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} il_\alpha \\ il_\beta \end{bmatrix} \tag{10}$$

Instantaneous active and reactive load currents and can also be decomposed into oscillatory and average terms $il_d = \tilde{il}_d + Il_d$, and $il_q = \tilde{il}_q + Il_q$. The first harmonic current of positive sequence is transformed to dc quantities, i.e., this constitutes the average current components. All higher order current harmonics including the first harmonic current of negative sequence 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. 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 a 2nd order high pass filter (HPF) with cut-off frequency of 100Hz and damping constant $\delta = 0.7$. Figure 5, shows the magnitude and phase response of the 2nd order high pass filter used for

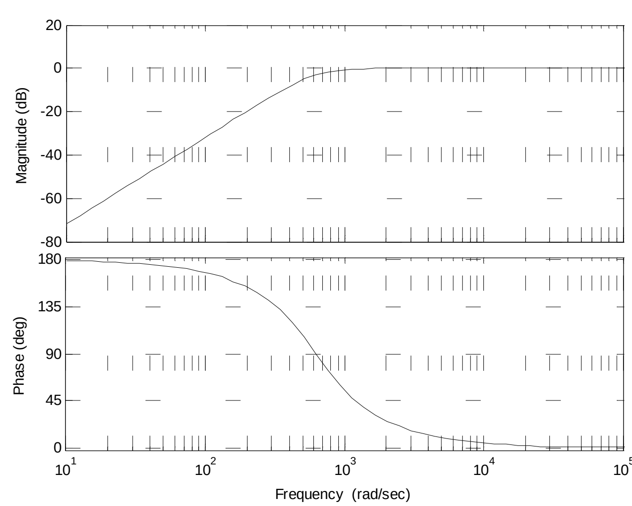

Figure 5: Magnitude and Phase Responce of 2nd Order HPF

attenuating all lower than cut-off frequencies having gain $k = 1$. Eliminating the average current components by HPF's the currents that should be compensated are obtained and finally, (11) and (8) calculate the converter currents in the system coordinates.

$$\begin{bmatrix} iC_\alpha \\ iC_\beta \end{bmatrix} = \frac{1}{\sqrt{V_\alpha^2 + V_\beta^2}} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} iC_d \\ iC_q \end{bmatrix} \qquad (11)$$

One of the characteristics of both methods is that the compensating currents are calculated directly from the mains voltages, enabling the methods to be frequency-independent.

4. GENERALIZED FRYZE CURRENT CONTROL THEORY

Despite of the usefulness and flexibility of the instantaneous power theory as a base for designing active filter controllers, other approaches may be found suitable, depending upon the objectives to be accomplished. For instance, the decomposition from the load current in to active and non active current, as results from current minimization method, can be used for designing controllers for shunt active filters. Controllers for the shunt active filters that guarantees compensated currents proportional to the supply voltages and can be implemented by using the concept of current minimization and generalized Fryze currents.

An advantage of the generalized Fryze current control is the reduced calculation effort, since it handles directly with abc phase voltages and line currents. The elimination of the Clarke transformation makes this control strategy very simple. The instantaneous equivalent conductance G is calculated from the instantaneous active three-phase power and the squared instantaneous aggregate voltage:

$$G_{eq} = \frac{V_a i_a + V_b i_b + V_c i_c}{V_a^2 + V_b^2 + V_c^2}$$

Then, the instantaneous active current can be calculated directly from the instantaneous conductance as:

$$\begin{aligned} i_{wa} &= G_{eq} V_a \\ i_{wb} &= G_{eq} V_b \\ i_{wc} &= G_{eq} V_c \end{aligned} \qquad (13)$$

Instantaneous conductance Geq varies if the voltages and current contain harmonics. Thus, the average conductance Geq is obtained passing it through 2nd order low pass filter with a cutoff frequency of 20 Hz. Figure 5, shows the magnitude and phase response of the 2nd order high pass filter used for attenuating all higher than the cut-off frequency of 20 Hz having gain $k = 1$.

$$i_{a,Comp}{*} = i_{wa} - i_{La} \qquad (14)$$

5. RESULTS AND ANALYSIS

In order to validate the results we have used PSIM software and the behaviour of the shunt Active Power Filter shown in Figure 14 for the different algorithms the results of the same are presented. The balanced and ideal sinusoidal source voltage condition considered. Figure (8) and (9), shows the performance of pq theory based strategy, Figure (10) and (11), shows the performance of instantaneous current component theory and Figure (12) and (13), shows the performance of Generalized Fryze current strategy. As expected, quite similar results are obtained from the first two control strategies.

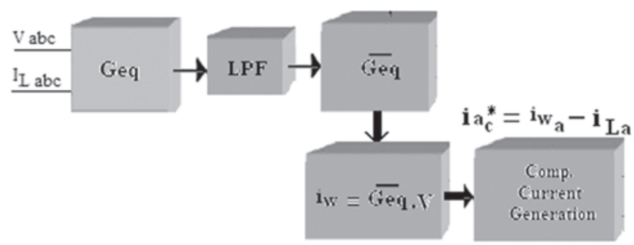

Figure 6: Generalized Fryze Currents Control Strategy for Shunt Current Compensation

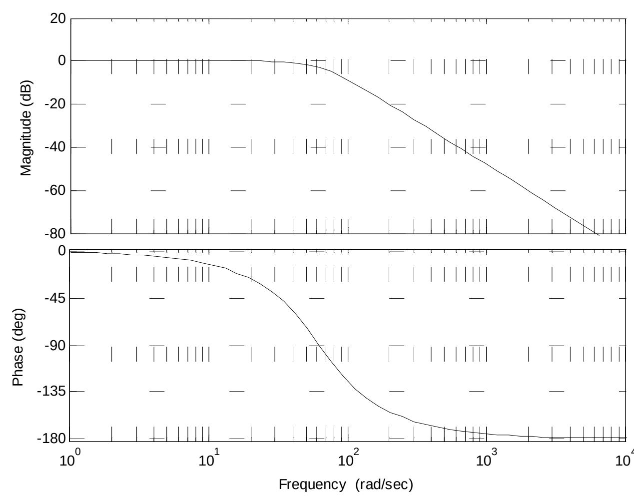

Figure 7: Magnitude and Phase Responce of 2nd Order LPF.

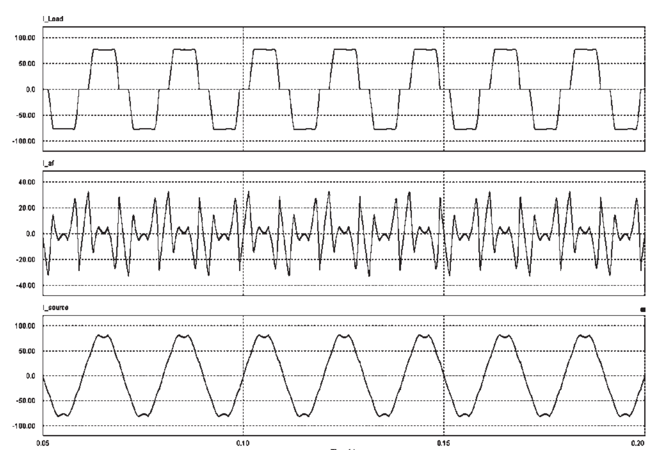

Figure 8: Performance of p-q Theory: (1) Load Current (2) Compensating Current (3) Source Current

The graphical chart-1, shows the different methods responsible for harmonic component reduction and source current THD improvement for non linear load conditions all the methods are suitable except fryze current control method where the current THD is above 5% so not as per IEEE–519 limit requires a special passive filter combination

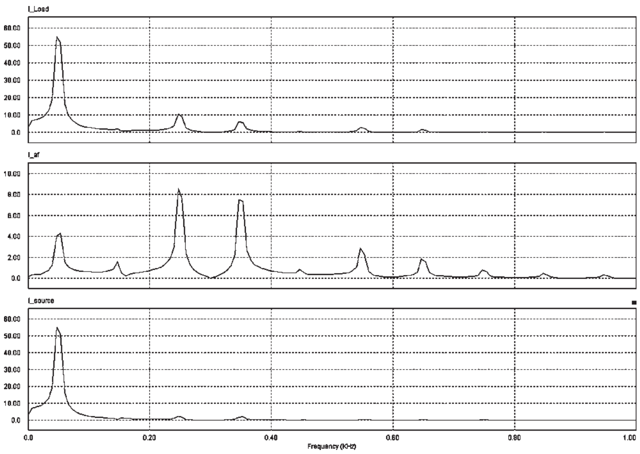

Figure 9: FFT Analysis of p-q Theory: (1) Load Current (2) Compensating Current (3) Source Current

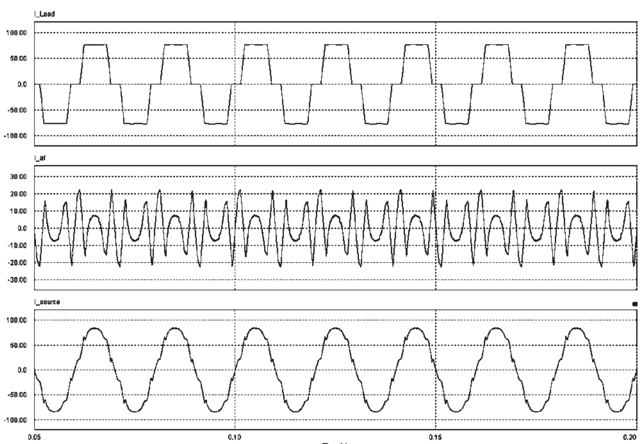

Figure 10: Performance of Current Component Theory: (1) Load Current (2) Compensating Current (3) Source Current

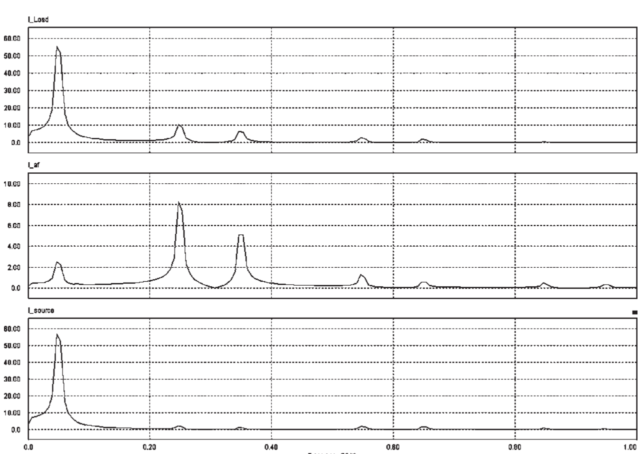

Figure 11: FFT Analysis of Current Component Theory: (1) Load Current (2) Compensating Current (3) Source Current

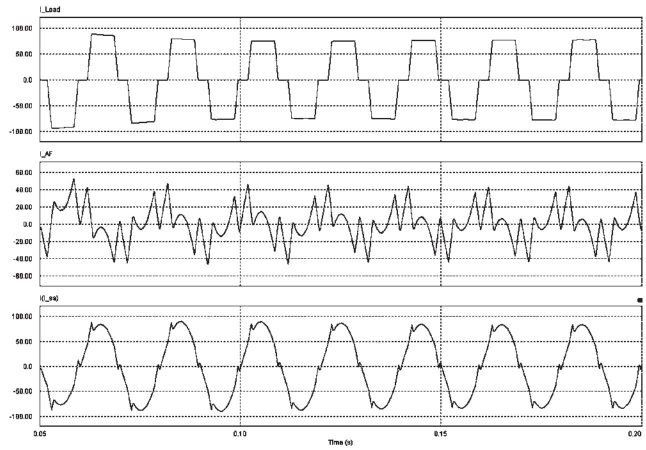

Figure 12: Performance of Generalized Fryze Current Control: (1) Load Current (2) Compensating Current (3) Source Current.

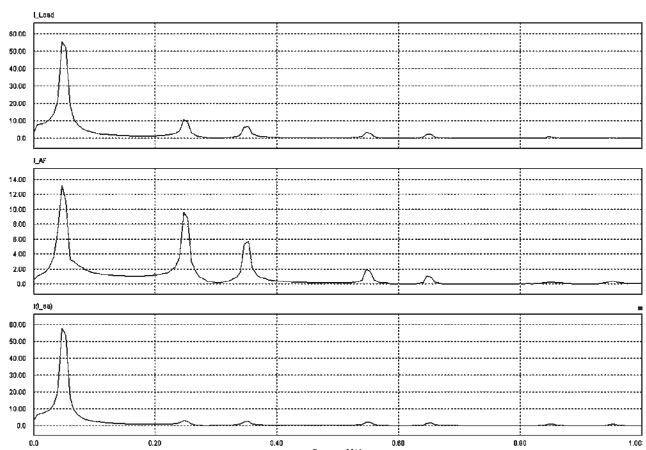

Figure 13: FFT Analysis of Generalized FRYZE Current Control: (1) Load Current (2) Compensating Current (3) Source Current.

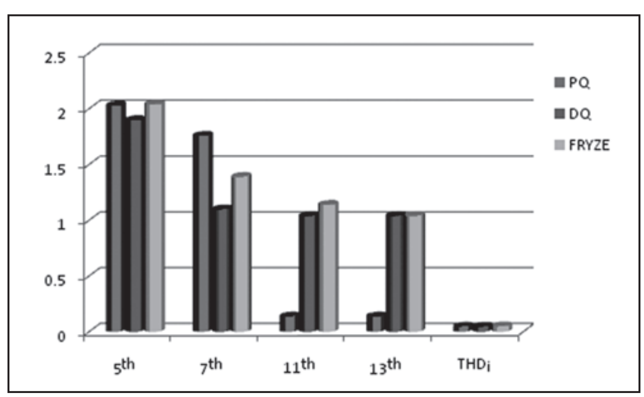

Figure 14: Graphical Chart of Harmonic Content and Source Current THD with Different Methods.

for specific harmonic reduction. Alos in case of distorted source voltage is distorted. Figure (6) and (7), shows the load current and source current and its FFT analysis based on instantaneous power theory, Figure 8 and 9, shows the load current and source current and its FFT analysis based on instantaneous current component theory and Figure 10 and 11, shows the load current and source current and its FFT analysis based on Fryze current control theory finally all three methods are being compared with basic direct fundamental current extraction method for the reference current generation.

Table 1
Results of the Considered Case

	Load Current	*Source Current (Amp)*		
	(Amp)	*PQ*	*DQ*	*FRYZE*
1st	54.6	54.5	55.23	56.7
5th	10.8	2.03	1.9	2.04
7th	6.3	1.76	1.1	1.39
11th	3.25	0.14	1.04	1.14
13th	2.85	0.14	1.04	1.04
THD_i	**24.2 %**	**4.9 %**	**4.78 %**	**5.1 %**

Table 2
Comparative Analysis of the Different Techniques

Parameters	*Without Compensation*	*PQ Theory*	*I_{d-q} Theory*	*FRYZE Current Theory*
VA	6171	6101	6080	6104
PF	0.907	0.951	0.989	0.979
DPF	0.983	0.999	0.999	0.996
THD_{is}	24.2 %	4.9 %	4.78 %	5.1 %
Time Response	-	50ms	50ms	10ms
Dynamic Response under Load Changes	-	Fast	Fast	Slow

6. CONCLUSION

This paper presents the comparison of three different real time reference generation techniques simulated using software PSIM 7.1.2 and analysed for the three wire shunt active power filters. The performance of AF in steady state condition is evaluated using FFT simulation. The compensation performance of the all the techniques are similar under ideal conditions, but under any other voltage conditions the average and oscillatory powers are disturbed by voltage harmonics and unbalanced voltage conditions, so neither method achieves total harmonic elimination. However, in spite of the error introduced in the determination of power components, the instantaneous current component method performance is always superior compared with the instantaneous power method but under the presence of unbalanced and voltage distortion, the current component algorithm presents the best performance. It is insensitive to voltage perturbations. It is fundamental to consider adequately the cut-off frequency in the filter used to extract the ac component in the different techniques. If the frequency is changed, the compensation performance is affected as well as the transient response of the control scheme. In the third method the fundamental pq theory was exploited and introduced into a minimization method, which has similar compensation characteristics. Advantage is reduced computational efforts with minimization of Clarke and park transformation. The generalised Fryze current control strategy has poor performance under distorted system voltages. Simulation results have determined that the instantaneous current component method provides good steady state and transient response for active filters in balanced and unbalanced systems respectively.

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