A Comparative Performance Analysis of Four Control Algorithms for a Three Phase Shunt Active Power Filter

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Abstract:

Shunt Active Power Filters (SAPFs) represent the most important and widely used filter in industrial purposes due to the fact that, they not only eliminate the harmonic current with a neglected amount of active fundamental current supplied to compensate system losses, but also they are suitable for a wide range of power ratings. One of the key issues for a proper implementation of an active filter is to use a good control algorithm for reference current generation. This paper presents a comparative analysis of the effectiveness of four approaches for determining the reference compensation currents of SAPF to maintain sinusoidal source currents supplied to nonlinear loads according to IEEE-519 standard. The approaches to be compared include the instantaneous reactive power theory, synchronous reference frame theory, synchronous detection method and perfect harmonic elimination method. Models of a power line with a nonlinear load using the above four approaches are developed using MATLAB-Simulink and are simulated for both balanced and unbalanced conditions.

Keywords: Shunt Active Power Filter, p-q method, i_d-i_q method, synchronous detection method, perfect harmonic cancellation

1. Introduction

The growing number of power electronics-based equipment has produced an important impact on the quality of electric power supply. Both industrial loads and domestic loads cause harmonics in the network voltages. At the same time, most of the equipment causing the disturbances is quite sensitive to deviations from the ideal sinusoidal line voltage. This harmonic distortion has traditionally dealt with the use of passive filters. However the application of passive filters has some drawbacks like over compensation of reactive power, creating resonance and its heavy and bulky. To overcome the above problems, power engineers developed a dynamic and adjustable solution to power quality problems. Such equipment as shown in fig. 1 is called an active filter and is able to compensate current and voltage harmonics. The basic principle of a shunt active power filter is that it generates a current equal and opposite in polarity to the harmonic current drawn by the load and injects it to the point of common coupling, thereby forcing the source current to be pure sinusoidal.

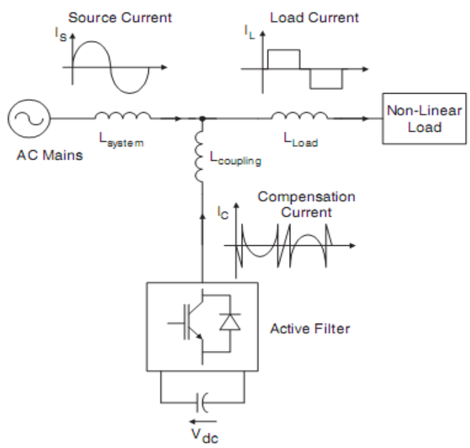

Fig. 1. Basic structure of a SAPF

Consequently, the characteristics and efficiency of harmonic compensation and its effectiveness depend on the control algorithm applied to calculate the load current harmonics. A number of active filter configurations and control strategies have been proposed in the last two decades to achieve the desired harmonic compensation level.

This paper presents a comparative analysis of four control strategies (p-q method, i_d-i_q method, synchronous detection method (SDM) and perfect harmonic cancellation (PHC) method) for the extraction of the reference currents for a shunt active power filter connected to a three phase system that supplies a nonlinear load. The comparison of the methods is made by simulations both under balanced and unbalanced conditions.

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2. Instantaneous p-q strategy

Instantaneous Reactive Power Theory (p-q) uses the Park Transform, given in Eqn. (2.1), to generate two orthogonal rotating vectors (α and β) from the three phase vectors (a, b and c)[1][2]. This transform is applied to the voltage and current and so the symbol x is used to represent v or i. This theory assumes balanced three phase loads and does not use the x0 term.

$$\begin{bmatrix} x_0 \\ x_\alpha \\ x_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \qquad (2.1)$$

Fig 2 shows the block diagram for an active power filter based on Instantaneous Reactive Power Theory. The supply voltage and load current are transformed into αβ quantities. The instantaneous active and reactive powers p and q are calculated from the transformed voltage and current as given in Eqn. (2.2).

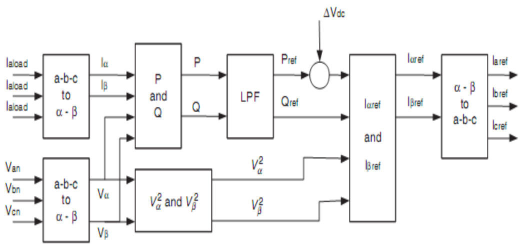

Fig.2. Block diagram of current reference generator using p-q theory

$$\begin{bmatrix} p = \bar{p} + \tilde{p} \\ q = \bar{q} + \tilde{q} \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (2.2)$$

The instantaneous active and reactive powers are filtered to leave the AC components. The compensating currents are determined by taking the inverse of eqn. (2.2) as given in eqn. (2.3).

$$\begin{bmatrix} i_\alpha^t \\ i_\beta^t \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \qquad (2.3)$$

The inverse Park transformation is then applied to eqn. (2.3) in order to get the standard three phase compensating current as given in eqn. (2.4).

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha^t \\ i_\beta^t \end{bmatrix} \qquad (2.4)$$

3. Synchronous Reference Frame

In this method, the load current is transformed into the conventional rotating frame dq [3]. The block diagram of a current reference generator that uses the synchronous reference frame algorithm is shown in fig. 3. The reference frame is synchronized with the ac mains voltage, and is rotating at the same frequency. If θ is the transformation angle, the transformation is defined by eqn. 3.1.

$$\begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{4\pi}{3}\right) \\ -\sin(\theta) & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{4\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \qquad (3.1)$$

where '*x*' denotes voltages or currents.

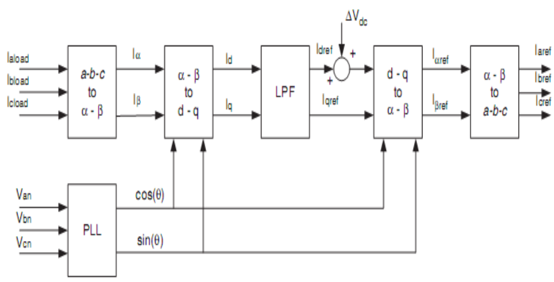

Fig.3.Block diagram of current reference generator using synchronous reference frame theory

To implement this theory, some kind of synchronism is obtained using a PLL circuit as shown in fig. 3. The fundamental for each is now a dc value with harmonics appearing as ripples. Harmonic isolation of the transformed signal is achieved by removing the dc offset. This is achieved using a low pass filter [4][5].

The compensation current in standard three phase form is obtained using inverse transformation as shown in eqn. (3.2)

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\omega t) & -\sin(\omega t) \\ 0 & \sin(\omega t) & \cos(\omega t) \end{bmatrix} \begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} \tag{3.2}$$

One of the most important characteristics of this algorithm is that the reference currents are obtained directly from the loads currents without considering the source voltages. This is an important advantage since the generation of the reference signals is not affected by voltage unbalance or voltage distortion, therefore increasing the compensation robustness and performance.

4. Synchronous Detection Method

In this algorithm, the three-phase source currents are assumed to be balanced after compensation [6]. The real power p(t) consumed by the load could be calculated from the instantaneous voltages and load currents as given by eqn. (4.1).

$$p(t) = \begin{bmatrix} v_{sa}(t) & v_{sb}(t) & v_{sc}(t) \end{bmatrix} \begin{bmatrix} i_{la}(t) \\ i_{lb}(t) \\ i_{lc}(t) \end{bmatrix} \tag{4.1}$$

where, $v_{sa}(t)$, $v_{sb}(t)$, $v_{sc}(t)$ are the instantaneous values of supply voltages and $i_{la}(t)$, $i_{lb}(t)$, $i_{lc}(t)$ are the instantaneous values of load currents. The average value Pdc is determined by applying p(t) to a low pass filter. The real power is then split into the three phases as given by eqn. (4.2)

$$P_a = \frac{P_{dc} \times V_{sma}}{V_{sma} + V_{smb} + V_{smc}}$$

$$P_b = \frac{P_{dc} \times V_{smb}}{V_{sma} + V_{smb} + V_{smc}}$$

$$P_c = \frac{P_{dc} \times V_{smc}}{V_{sma} + V_{smb} + V_{smc}}$$

Thus for purely sinusoidal balanced supply voltages:

$$P_a = P_b = P_c = \frac{P_{dc}}{3} \tag{4.3}$$

where,

$$P_a = V_{sa} \times I_{sa} = \frac{V_{sma}}{\sqrt{2}} \times \frac{I_{sma}}{\sqrt{2}} = \frac{V_{sma} \times I_{sma}}{2} \tag{4.4}$$

$$\therefore I_{sma} = \frac{2 \times P_a}{V_{sma}} \tag{4.5}$$

Thus the reference source current is given by eqn. (4.6a), (4.6b), and (4.6c).

$$i_{sa}(t) = \frac{2 \times v_{sa}(t) \times P_a}{V_{sma}^2} \tag{4.6a}$$

$$i_{sb}(t) = \frac{2 \times v_{sb}(t) \times P_b}{V_{smb}^2} \tag{4.6b}$$

$$i_{sc}(t) = \frac{2 \times v_{sc}(t) \times P_c}{V_{smc}^2} \tag{4.6c}$$

where, Vsma, Vsmb, Csmc are the amplitudes of the supply voltages. The compensation currents are then calculated using eqn. (4.7a), (4.7b) and (4.7c)

$$i_{ca}(t) = i_{sa}(t) - i_{la}(t) \tag{4.7a}$$

$$i_{cb}(t) = i_{sb}(t) - i_{lb}(t) \tag{4.7b}$$

$$i_{cc}(t) = i_{sc}(t) - i_{lc}(t) \tag{4.7c}$$

This method can be extensively used for compensation of reactive power, current imbalance and mitigation of current harmonics. It is the simplest method as it requires minimum calculations. However this method suffers a drawback from individual harmonic detection and its mitigation.

5. PHC Strategy

The Perfect Harmonic Cancellation (PHC) method can be regarded as a modification of the three previous theories. Its objective is to compensate all the harmonic currents and the fundamental reactive power demanded by the load in addition to eliminating the imbalance. The source current will therefore be in phase with the fundamental positive-sequence component of the voltage at the PCC [7]. In the proposed PHC strategy the load active power is calculated as in eqn. 5.1.

$$P(t) = i_a e_a + i_b e_b + i_c e_c = P_{dc} + P_{ac} \tag{5.1}$$

Then, only the fundamental components of the load voltages are considered for determining the desired currents. Therefore,

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \frac{P_{dc}}{(\overline{e}_\alpha)2 + (\overline{e}_\beta)2} \begin{bmatrix} 0 \\ e_\alpha \\ e_\beta \end{bmatrix} \qquad (5.2)$$

where $\overline{e}_\alpha$ and $\overline{e}_\beta$ are the fundamental components of the load voltages and can be obtained using a positive sequence detector. Also, P_{dc} is filtered from P(t) using a simple low pass filter (LPF). The desired currents calculated using this method are symmetrical and sinusoidal.

6. Simulation

The model of the SAPF is developed for all control strategies using MATLAB Simulink block. The simulation studies are carried out for the system parameters shown in Table.1.All the models developed are simulated for two different supply conditions, which are balanced normal sinusoidal supply and unbalanced sinusoidal supply.

System Source voltage	230V
System frequency	50Hz
DC link capacitor	40mF
Series Inductor	3.35mH
Source Inductance	1mH
Resistive Load(three phase diode bridge rectifier)	25Ω

Table1. System parameters

7. Simulation Results

The simulation result is divided into two cases of different supply conditions; the balanced sinusoidal supply and the unbalanced sinusoidal supply. Unbalance is created by reducing one of the phase of the source voltage by 20% than the others (phase A).The waveforms of the input voltage, uncompensated load current, compensated source current, filter current and the percentage of total harmonic distortion for both cases are presented

Case I: Balanced sinusoidal supply

- **p-q method**

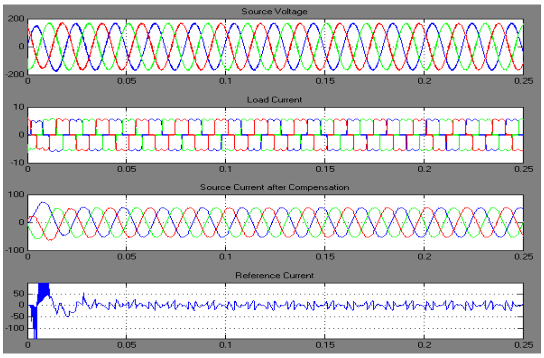

Fig. 4. The current waveforms

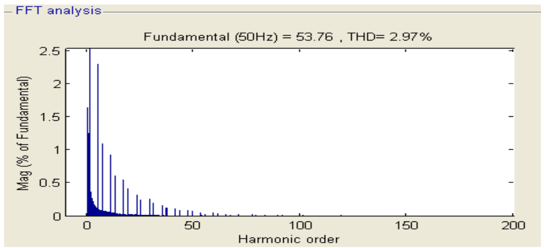

Fig. 5. %THD of source current

- **i_d-i_q method**

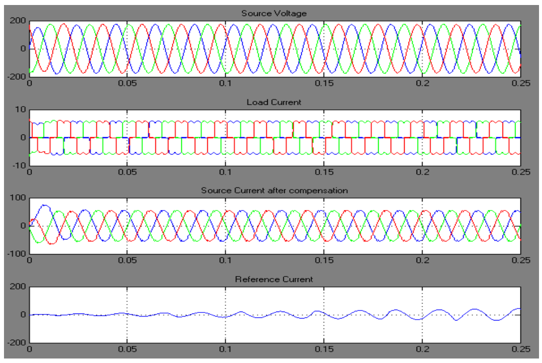

Fig. 6. The current waveforms

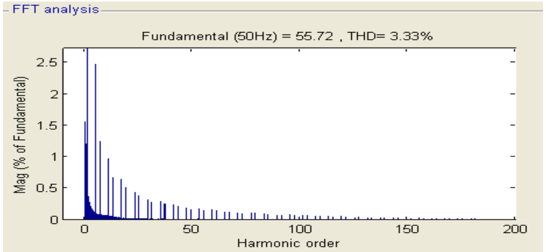

Fig. 7. %THD of source current

- **SDM method**

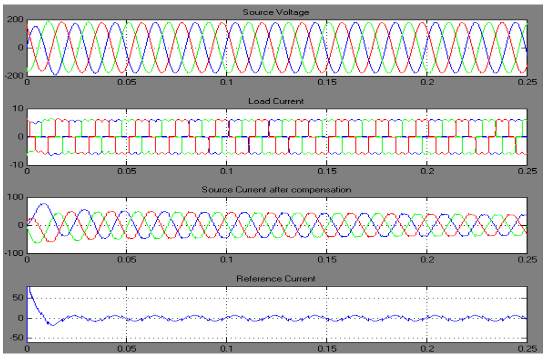

Fig. 8. The current waveforms

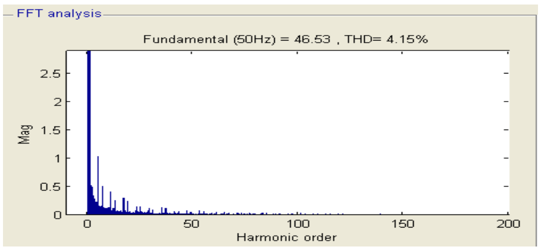

Fig. 9. %THD of source current

- **PHC strategy**

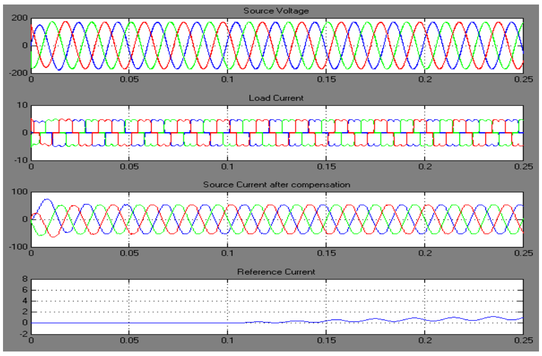

Fig. 10. The current waveforms

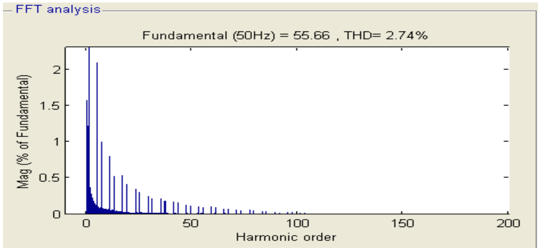

Fig. 11. %THD of source current

Case II: Unbalanced sinusoidal supply

- **p-q method**

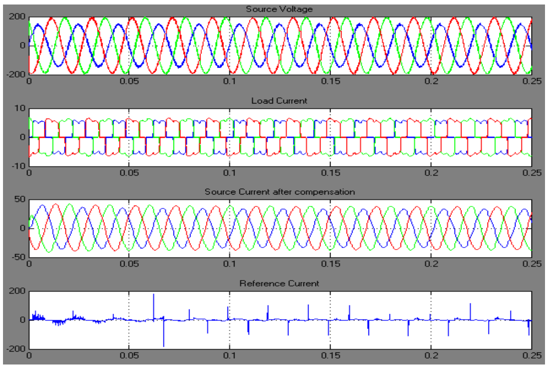

Fig. 12. The current waveforms

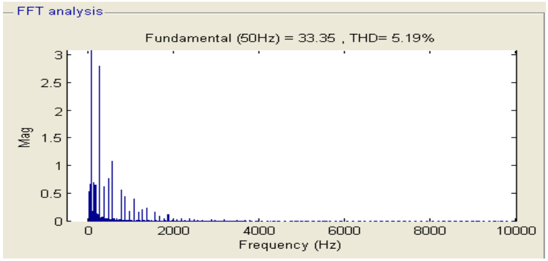

Fig. 13. %THD of source current

- **i_d-i_q method**

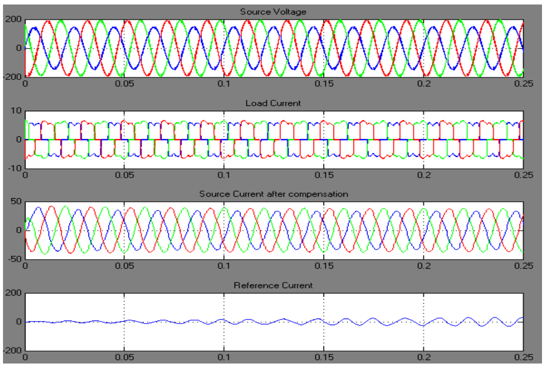

Fig.14. The current waveforms

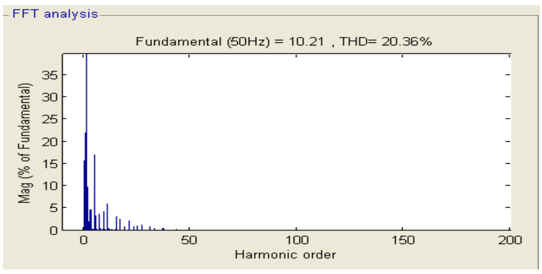

Fig. 15. %THD of source current

Load Condition	Uncompensated	p-q	**Synchronous reference Frame**	**Synchronous Detection**	**Perfect Harmonic Cancellation**
	I_{source} %THD	$I_{ompensated}$ %THD	$I_{compensated}$ %THD	$I_{compensated}$ %THD	$I_{compensated}$ %THD
Balanced Main Voltages	29.62	2.97	3.33	4.15	2.74
Unbalanced Main Voltages	32.25	5.19	20.37	18.96	2.99

- **SDM method**

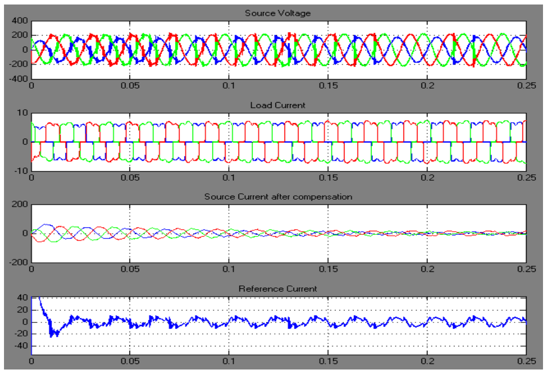

Fig. 16. The current waveforms

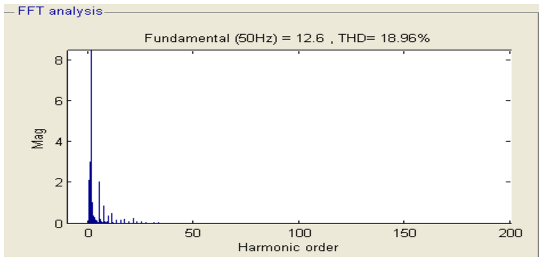

Fig. 17. %THD of source current

- **PHC strategy**

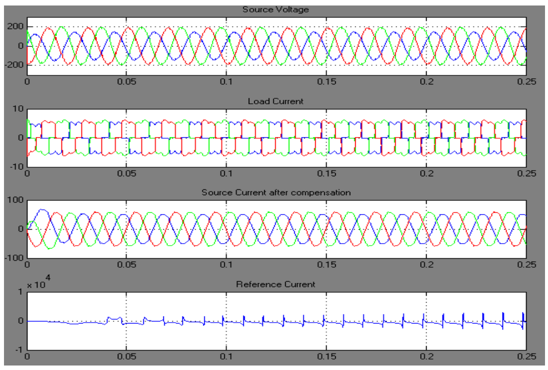

Fig. 18. The current waveforms

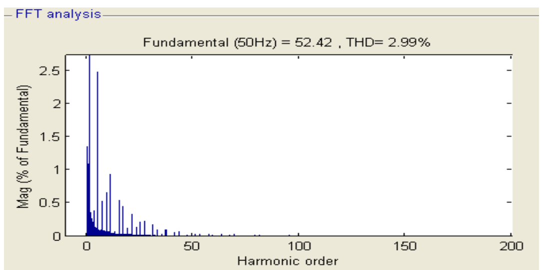

Fig. 19. %THD of source current

The overall performance comparison of the four control strategies under balanced and unbalanced conditions are presented in tableII.

TableII Performance Comparison

8. Conclusion

The comparison of four control techniques implemented for the generation of the reference current for shunt active power filters was presented. Figs. 4-19 shows the simulated results of various control strategies. The compensation performance of the different techniques is almost similar under ideal balanced conditions and they satisfy IEEE-519 standard. Under unbalanced conditions, it was shown that the p-q strategy, i_d-i_q strategy and the synchronous detection method are most sensitive to distortion and imbalance in the voltages at the PCC.

The simulations shows that, if one seeks compliance with harmonics standard, imbalance elimination and reactive power compensation, PHC strategy is capable of compensating action under any conditions of use.

9. References

[1] H. Akagi, Y. Kanazawa, and A. Nabae, "Instantaneous reactive power compensators comprising switching devices without energy storage components," IEEE Trans. Ind. Appl., vol. IA-20, no. 3, pp. 625–630, May/Jun. 1984.

[2] J. Afonso, C. Couto, and J. Martins, "Active filters with control based on the p–q theory," IEEE Ind. Electron. Soc. Newslett., pp. 5–11, Sep. 2000.

[3] V. Soares, P. Verdelho, and G. D. Marques, "An instantaneous active and reactive current component method for active filters," IEEE Trans Power Electron., vol. 15, no. 4, pp. 660–669, Jul. 2000.

[4] L.Rolim, D.Costa, and M.Aredes "Analysing and Software Implementation of a Robust Synchronizing PLL Circuit Based on the pq Theory " IEEE Trans on ind elctronics vol 53 N◦6 .pp 1919-1926.December 2006

[5] A. Cavallani and G. C. Montarani, "Compensation strategies or shunt active-filter control," IEEE Trans. Power Electron., vol. 9, no. 6, pp. 587–593, Nov. 1994.

[6] Moleykutty George and Karthik Prasad Basu, " Three Phase Shunt Active Power Filter", American Journal of Applied Sciences", vol. 5, no. 8, pp. 909-916, 2008.

[7] Gary W.Chang and Tai-Chang Shee, "A Comparative Study of Active Power Filter Reference Compensation Approaches", IEEE Trans. Power Electron, vol. 2, pp. 1017-1021, 2002.

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