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Comparison of Control Strategies for Shunt Active Power Filter under Different Load Conditions

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Abstract: Harmonic injection in supply current is most common problem arising in supply network because of the increased population of nonlinear loads. This paper present a comparative study between two different control strategies to determine the compensating currents for a three phase three wire Shunt Active Power Filter(SAPF). The first strategy is based on the instantaneous real and imaginary powers theory known as p-q theory, the second is Generalized Instanteneous Power Theory(GIPT). The two control strategies are applied to a three-wire shunt active power filter for eliminating load current harmonics, reactive power compensation and load balancing. The validity of the proposed control scheme is verified by the simulation study.

Index Terms: Active Power, Harmonic Elimination, Non-linear load, Load Balancing.

I. INTRODUCTION

The increased severity of harmonic pollution in power networks with the development of power semiconductors and power-electronics application techniques has attracted the attention to develop dynamic and adjustable solutions to the power quality problems. Control of these harmonic perturbations by passive filters can generate additional resonance, which could result in destruction of these filters. This has lead to development of active filters. Shunt active filters have been recognized as a good solution to current harmonic and reactive power compensation of non-linear loads [1]. Fig.1 shows a typical system configuration of a three-phase three-wire; shunt APF with a voltage source inverter. 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.

Instantaneous power compensation theory is recognized as one of the best methods. Instantaneous real and imaginary powers have first been defined in the time domain by *p –q* theory, and their concept has been successfully applied to harmonic/reactive current control in three-phase three-wire systems [2-3]. In *p –q* theory, voltages and currents in a three-phase three wire system are transformed into two-phase current/voltage components on orthogonal α– β coordinates, and then the instantaneous real and imaginary powers can be calculated without any time delay from the two-phase components.

A generalized theory of instantaneous reactive power has been proposed for three-phase power systems. The generalized theory is valid for sinusoidal or non sinusoidal and balanced or unbalanced three-phase systems, with or without zero-sequence currents and/or voltages [4].In this paper generalized definition of instantaneous active, reactive and apparent power in three-phase system is presented. By directly taking the instantaneous voltage and current as two vectors, the instantaneous reactive quantity is considered as the second order asymmetrical tensor resulting from the outer-product operation of voltage and current vectors. This definition is further extended for Active Power Line Conditioners (APLCs) applications by decomposing current into separate component representing different parts of the power.

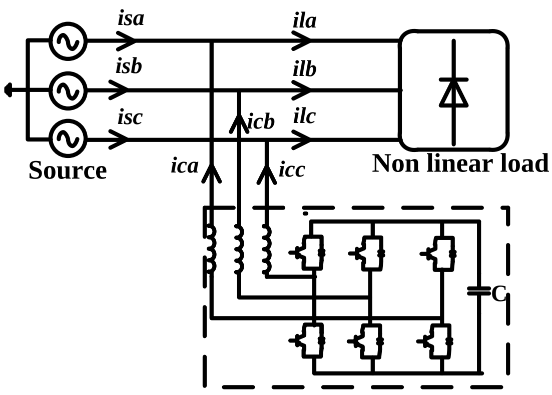

Fig. 1 System diagram of a VSI-SAPF

In this paper results obtained for shunt active power filter using GIPT are compared with that obtained by more widely used instantaneous p-q theory for the known three phase conditions. Application to calculate references for active power filter are also presented for different applications like harmonic elimination, reactive power compensation and load balancing under sinusoidal supply condition.

II. P-Q THEORY

The instantaneous *p-q* method is one of the first compensation schemes developed by Akagi [1].According to this theory active filter currents are obtained from the instantaneous active and reactive powers of the nonlinear load. This is achieved by previous calculation of the mains voltages and the nonlinear load currents in a stationary reference frames, i.e., in αβ0 components by (1) and (2) which is named as the Clarke transformation.

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2)$$

No zero-sequence components exist in a three-phase three-wire system, so that i_0 and v_o can be eliminated from the above equation (1) & (2).

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (4)$$

The conventional instantaneous real power in three phase circuit is defined by [1] as the summation of the products of voltages and current on same axis.

$$p = v_a i_a + v_b i_b + v_c i_c = v_\alpha i_\alpha + v_\beta i_\beta \quad (5)$$

For the instantaneous reactive power the authors [1] introduced the instantaneous imaginary power space vector defined by

$$q = v_\alpha i_\beta - v_\beta i_\alpha \quad (6)$$

The instantaneous real power p and the instantaneous imaginary power q consumed by the nonlinear load are written in matrix form as follows,

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \quad (7)$$

Fig. 2(a) illustrates the control block diagram using *p-q* theory. In the nonlinear load case both powers are decomposed into oscillatory (denoted by ~) and average (DC) component (denoted by -). The DC component represents the fundamental power, whereas the oscillating component is related with the harmonic power.

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} + \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \quad (8)$$

For harmonic elimination from nonlinear load, the oscillating term of p and q have to be removed. So the powers to be compensated chosen as:

$$p_c = -\tilde{p}\ , \qquad q_c = -\tilde{q} \quad (9)$$

For reactive power compensation, the oscillating term of p and q have to be removed. So the powers to be compensated chosen as:

$$p_c = 0\ , \qquad q_c = -q \quad (10)$$

For harmonic elimination and reactive power compensation from nonlinear load, the oscillating term of p and total q have to be removed. So the powers to be compensated chosen as:

$$p_c = -\tilde{p}\ , \qquad q_c = -q \quad (11)$$

The compensation currents in α-β quantities then is,

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p_c \\ q_c \end{bmatrix} \quad (12)$$

By performing the inverse transformation, the three-phase compensation is obtained by (12).

$$\begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} = k^T \begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} \quad (13)$$

Where $k^T = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}$

III. GENERALIZED INSTANTANEOUS POWER THEORY

For a three-phase system, the instantaneous quantities of load voltage and currents are expressed as

$$\vec{v} = [v_a,\ v_b,\ v_c]^T, \vec{\imath} = [i_a,\ i_b, i_c\ ]^T \quad (14)$$

Loads instantaneous active power *'p'* is defined as the inner product of voltage and current vectors.

$$p(t) = \vec{v}(t) \cdot \vec{\imath}(t) \quad (15)$$

Where "." denotes the dot (internal) product, or scalar product of vectors. Equation (15) can also be expressed in the conventional definition,

$$p(t) = v_a i_a + v_b i_b + v_c i_c \quad (16)$$

Loads instantaneous reactive power *'$\vec{q}$'* is defined as the outer product of voltage and current vector.

$$\vec{q}(t) = \vec{v}(t) \times \vec{\imath}(t) \quad (17)$$

Where "×" the cross (exterior) product of vectors or vector product. Vector q is designated as the instantaneous reactive (or nonactive) power vector of the three phase circuit. The outer product is defined by means of the tensor product in the following way.

$$\vec{v}(t) \times \vec{\imath}(t) = \vec{\imath} \otimes \vec{v} - \vec{v} \otimes \vec{\imath} \quad (18)$$

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The tensor product of current vector over voltage vector is:

$$\vec{\imath} \otimes \vec{v} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \begin{bmatrix} v_a & v_b & v_c \end{bmatrix} = \begin{bmatrix} i_a v_a & i_a v_b & i_a v_c \\ i_b v_a & i_b v_b & i_b v_c \\ i_c v_a & i_c v_b & i_c v_c \end{bmatrix} \quad (19)$$

The tensor product of voltage vector over current vector is:

$$\vec{v} \otimes \vec{\imath} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \begin{bmatrix} i_a & i_b & i_c \end{bmatrix}$$
$$\vec{v} \otimes \vec{\imath} = \begin{bmatrix} v_a i_a & v_a i_b & v_a i_c \\ v_b i_a & v_b i_b & v_b i_c \\ v_c i_a & v_c i_b & v_c i_c \end{bmatrix} \quad (20)$$

Using Equation (18), (19) and (20) into (17),and hence

$$\vec{q}(t) = \begin{bmatrix} o & i_a v_b - v_a i_b & i_a v_c - v_a i_c \\ i_b v_a - v_b i_a & o & i_b v_c - v_b i_c \\ i_c v_a - v_c i_a & i_c v_b - v_c i_b & o \end{bmatrix}$$
$$\vec{q}(t) = \begin{bmatrix} 0 & -q_{ab} & q_{ca} \\ q_{ab} & 0 & -q_{bc} \\ -q_{ca} & q_{bc} & 0 \end{bmatrix} \quad (21)$$

With each components being as:

$$q_{ab} = v_a i_b - v_b i_a$$
$$q_{bc} = v_b i_c - v_c i_b$$
$$q_{ca} = v_c i_a - v_a i_c$$

'$\vec{q}$' is denoted as instantaneous reactive tensor and its norm is defined as instantaneous reactive power

$$\parallel \vec{q} \parallel = \sqrt{q_{ab}^2 + q_{bc}^2 + q_{ca}^2} \quad (22)$$

In turn, we define the instantaneous active current vector '$\vec{\imath_p}$', the instantaneous reactive current vector '$\vec{\imath_q}$',

$$\vec{\imath_p} = [i_{pa}, i_{pb}, i_{pc}]^T = \frac{\vec{v}}{\parallel \vec{v} \parallel^2} p(t) = \frac{p(t)}{\parallel \vec{v} \parallel^2} [v_a, v_b, v_c]^T \quad (23)$$

$$\vec{\imath_q} = [i_{qa}, i_{qb}, i_{qc}]^T = \frac{\vec{q}(t) \times \vec{v}(t)}{\parallel \vec{v} \parallel^2} = \frac{1}{\parallel \vec{v} \parallel^2} \begin{bmatrix} 0 & -q_{ab} & q_{ca} \\ q_{ab} & 0 & -q_{bc} \\ -q_{ca} & q_{bc} & 0 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (24)$$

Where, '$\vec{\imath_p}$' is denoted as instantaneous active current tensor and its norm is defined as instantaneous active current, '$\vec{\imath_q}$' is denoted as instantaneous reactive current tensor and its norm is defined as instantaneous reactive current.

$$\parallel \vec{\imath_p} \parallel = \sqrt{{i_{pa}}^2 + {i_{pb}}^2 + {i_{pc}}^2}$$
$$\parallel \vec{\imath_q} \parallel = \sqrt{{i_{qa}}^2 + {i_{qb}}^2 + {i_{qc}}^2} \quad (25)$$

The three-phase compensation current is the sum of the instantaneous active current vector '$\vec{\imath_p}$', the instantaneous reactive current vector '$\vec{\imath_q}$'

$$\vec{\imath_c} = [i_{ac}, i_{bc}, i_{cc}]^T = \vec{\imath_{pc}} + \vec{\imath_{qc}} = [i_{pac} + i_{qac}, i_{pbc} + i_{qbc}, i_{pcc} + i_{qcc}]^T \quad (26)$$

Fig. 2(b) illustrates the control block diagram using GIPT theory. When unbalanced nonlinear load is considered, the equation (8) is modified as:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} P_+ + P_{UB} \\ \bar{q} \end{bmatrix} + \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \quad (27)$$

Where P_+ is balanced active power and P_{UB} is an unbalanced active power. The powers to be compensated chosen as:

$$p_c = -(P_{UB} + \tilde{p}) = -(p - P_+)$$
$$q_c = -q \quad (28)$$

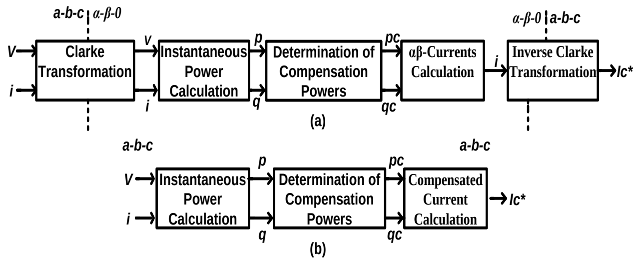

Fig. 2 Control algorithm (a) p-q theory (b) GIPT

IV. SIMULATION RESULTS

A simulation model has been developed for three-phase shunt active power filter using *p-q* theory and GIPT in PSIM Software. Table-I shows the parameters of both configurations.

Table I. Common parameters

Supply Voltage	400 V(Line to Line), 50Hz
Source Impedance	0.1mH, 0.5Ω
Shunt APLC Inductor	0.5mH
EMI Filter	Lf-1mH,Cf-2uF,Rf=0.1Ω
Switching Frequency	20 KHz
Load-1	Three phase Diode bridge rectifier with 50 Amp constant current source
Load-2	Three phase Linear RL load(R-1Ω, L-10mH)
Load-3	Diode bridge rectifier with 50 Amp constant current source and Unbalanced RL load(Ra-50Ω,La-12mH,Rb-20Ω,Lb-2.5mH,Rc-100Ω,Lc-27mH)

Fig. 3 and fig.6 shows simulation waveforms for mitigating supply current harmonics by p-q theory and GIPT respectively. It is observed that load current harmonics are almost removed from all three-phase supply current by both methods as shown in Fig. 3(d) and Fig. 6(d). Fig. 4 and Fig.7 shows simulation waveforms for reactive power compensation by p-q theory and GIPT respectively. It is observed that both methods are very effective for reactive power compensation and hence supply power factor improves from 0.3(lag) to 0.99(lag) by both methods. Fig. 5 shows the simulation waveform

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for load balancing using p-q theory. It is observed that when three phase unbalanced non-linear load is applied to balanced sinusoidal supply, the p-q theory is not effective for load balancing and hence three phase supply current is unbalanced as shown in Fig. 5(c). Fig. 8 shows the simulation waveform for load balancing using GIPT. It is observed that when three phase unbalanced non-linear load is applied to balanced sinusoidal supply, the GIPT is effective for load balancing. The three phase supply current is balanced and sinusoidal as shown in Fig. 8(c).

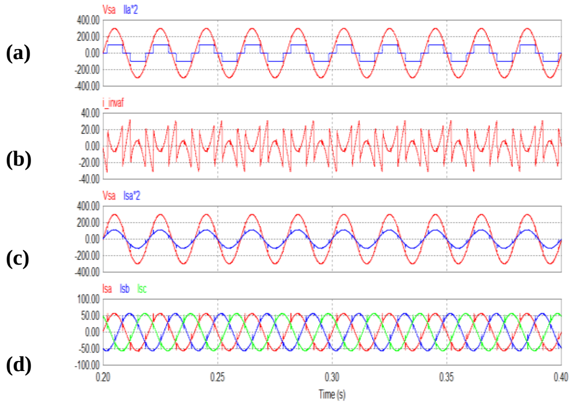

Fig. 3 Simulation waveform for Load-1 using *p-q* theory (a) load voltage and load current of phase-a (b) reference current (c) source voltage and source current of phase-a (d) three phase source current

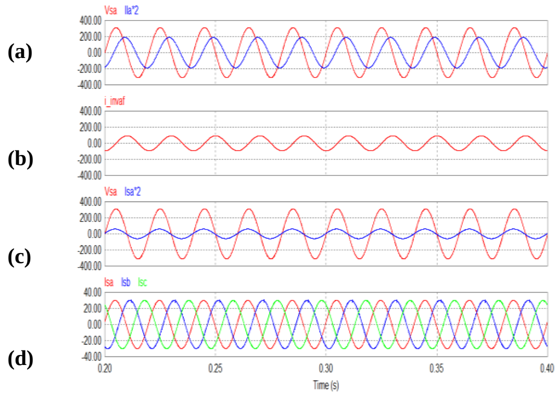

Fig. 4 Simulation waveform for Load-2 using *p-q* theory (a) load voltage and load current of phase-a (b) reference current (c) source voltage and source current of phase-a (d) three phase source current

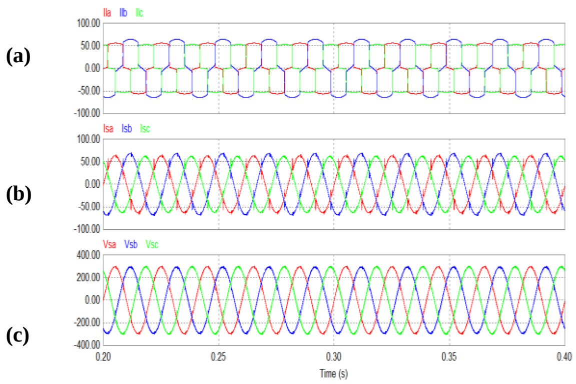

Fig. 5 Simulation waveform for Load-3 using *p-q* theory (a) three phase load current (b) three phase source current (c) three phase source voltage

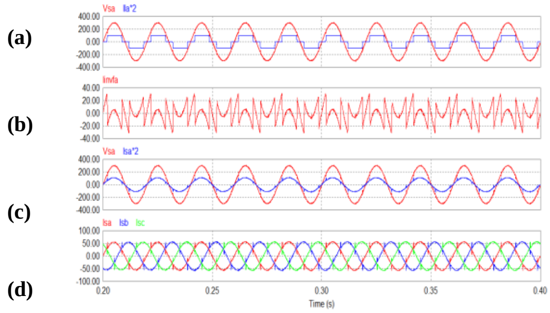

Fig. 6 Simulation waveform for Load-1 using GIPT (a) load voltage and load current of phase-a (b) reference current (c) source voltage and source current of phase-a(d) three phase source current

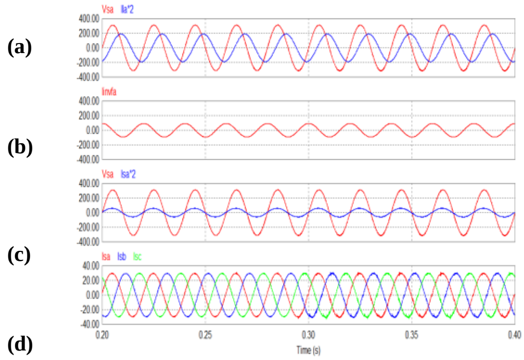

Fig. 7 Simulation waveform for Load-2 using GIPT (a) load voltage and load current of phase-a (b) reference current (c) source voltage and source current of phase-a (d) three phase source current

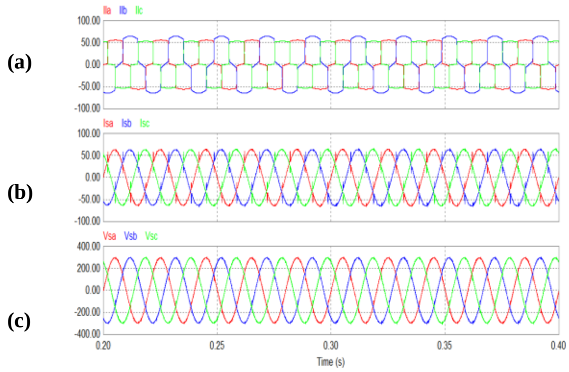

Fig. 8 Simulation waveform for Load-3 using GIPT (a) three phase load current (b) three phase source current (c) three phase source voltage

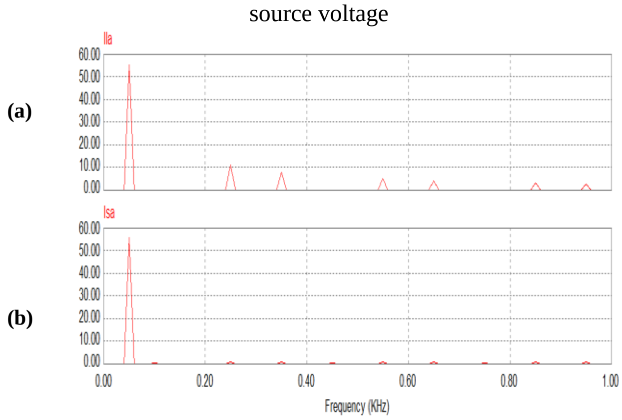

Fig. 9 Harmonic spectrum for Load-1 using *p-q* theory (a) load current of phase-a (b) source current of phase-a

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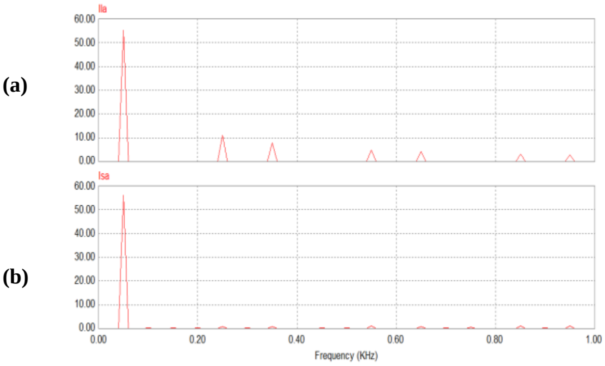

Fig. 10 Harmonic spectrum for Load-1 using GIPT (a) load current of phase-a (b) source current of phase-a

Fig. 9 and Fig.10 shows the FFT analysis of the supply current and load current by *p-q* theory and GIPT. It shows that amplitude of different- order harmonic is reduced. The supply current THD reduces from ***29.47% to 7.38%*** and the supply current THD reduces from ***29.47% to 6.4%*** with the use of *p-q* theory and GIPT respectively for load-1.

Table II Comparison of the two theories

Comparison items	p-q theory	GIPT
Harmonic elimination	Yes	Yes
Reactive power compensation	Yes	Yes
Load balancing	No	Yes
Calculation steps(Multiply)	23	9
Reference power control	Yes	Yes
Reference current control	No	No
Freedom of current control	2(+)	2

Table II shows the comparison results for the two power theories. After measuring the system voltages and currents *p–q* theory requires around 23 multiplication steps to decide the reference currents, while GIPT requires just around 9 multiplication steps. Harmonic elimination, Reactive power compensation and load balancing is possible through GIPT.

V. CONCLUSION

The increased use of power electronic equipments in the power system has a profound impact on power quality. In this paper mitigation of supply current harmonics, reactive power compensation and load balancing is done by *p-q* theory and GIPT. Different simulation results are studied on both these control theories. The following conclusions are made.

1. Theoretical study of *p-q* theory and GIPT is done.
2. Both theories are very effective in eliminating supply current harmonics and reactive power compensation.
3. Significant reduction in individual harmonic component is possible with both control theory.
   (i)The supply current THD reduces from ***29.47% to 7.38%*** with use of *p-q* theory, and
   (ii) The supply current THD reduces from ***29.47% to 6.4%*** with use of GIPT.
4. Load balancing is not possible through p-*q* theory, while GIPT provides load balancing.

REFERENCES

[1] Vadat M Karsh, Mehmet Tumay and Berrin Susluoglu, " An Evaluation of Time Domain Techniques for compensating current of shunt active power filters", IEEE Transactions on Power Electronics, vol. 10, pp.307, 2002.
[2] H. Akagi, Y. Kanazawa, and A. Nabae, "Instantaneous Reactive Power Compensators Comprising Switching Devices without Energy Storage Components," IEEE Transactions on Industry Applications, vol. 1A-20, pp. 625, May-June 1984
[3] M. Aredes and E. H. Watanabe, "New control algorithms series, and shunt three-phase four-wire active power filters," in IEEE PES Winter Meeting, 1995.
[4] F. Z. Peng and J. S. Lai, "Generalized instantaneous reactive power theory for three-phase power systems,"IEEE Transactions *Instrum. Meas.*,vol. 45, no. 1, pp. 293–297, 1996. [5] M. Aredes, J. Häfner, and K. Heumann, "Three-Phase Four-Wire Shunt Active Filter Control Strategies," IEEE Transactions on Power Electronics, vol. 12, pp. 311, March 1997
[6] C. L. Chen, C. E. Lin, and C. L. Huang, "An Active Filter for Unbalanced Three-Phase System Using Synchronous Detection Method, " in Proc. IEEE PESC'94, 1994, pp. 1451
[7] W. Chang, T. Shee, "A Comparative Study of Active Power Filter Compensation Approaches,'' IEEE Power Engineering Society Summer Meeting, vol. 2, pp. 1017, 2002
[8] F. Peng, H. Akagi, and A. Nabae, " A Study of Active Power Filters Using Quad-Series Voltage-Source PWM Converters for Harmonic Compensation,'' IEEE Transactions on Power Electronics, vol. 5, pp. 9-15, Jan. 1990
[9] H. Akagi, Y. Kanazawa, and A. Nabae, "Instantaneous reactive power compensators comprising switching devices without energy storage components," IEEE Transactions. Ind. Applicat., vol. 20, pp. 625–630,May/June 1984.
[10] A. Nabae and T. Tanaka, "A new definition of instantaneous active reactive current and power based on instantaneous space vectors on polar coordinates in three-phase circuits," presented at the IEEE/PES Winter Meeting, Paper 96 WM 227-9 PWRD, 1996.
[11] Herrera, R.S., Salmeron, P., Vazquez, J.R., Litran, S.P., Perez, A., "Generalised instantaneous reactive power theory in poly-phase power systems", 13th European Conference on Power Electronics and Applications, 2009. EPE '09. pp. 1 – 10.

