Comparison of Reference Compensating Current Estimation Techniques for Shunt Active Filter

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Abstract:
A shunt active filter injects a suitable non-sinusoidal current (compensating current) into the system at the point of common coupling and makes the source current sinusoidal. This paper presents a performance comparison of five different methods of estimating reference-compensating current for a three-phase shunt active power filter. The techniques compared are Instantaneous Active and Reactive power p-q method, Instantaneous Power Balance method, Instantaneous Active and Reactive current component id-iq method, Fourier series method and DC-link voltage regulation method. Their performance is investigated under ideal (balanced and sinusoidal), non-ideal (un-balanced and distorted) supply voltage conditions and at different load conditions. A three-phase six-pulse converter with R-L load is considered as the non-linear load. The MatLab/simulink simulation results are presented to validate and compare the control techniques in transient and steady state conditions.

Key words: Power quality, Active power filter, Comparative analysis, Harmonic and Reactive power compensation

1 Introduction

The proliferation of power electronic converters has led to the degradation of the power quality. The performance of SAPF depends on the method of extraction of the reference compensating current. This reference current and the actual SAPF current is given to a hysteresis based, carrier-less PWM current controller to generate the switching signals of the inverter.

Figure 1 shows the SAPF, which is controlled to supply a compensating current i_c at the point of common coupling (PCC) and cancels current harmonics on the supply side. Now, the source current i_s will be sinusoidal and in-phase with the supply voltage V_s. The organization of this paper is as follows. The different methods of estimating reference-compensating current are discussed and their performance is compared under ideal and non-ideal mains voltage at different load conditions.

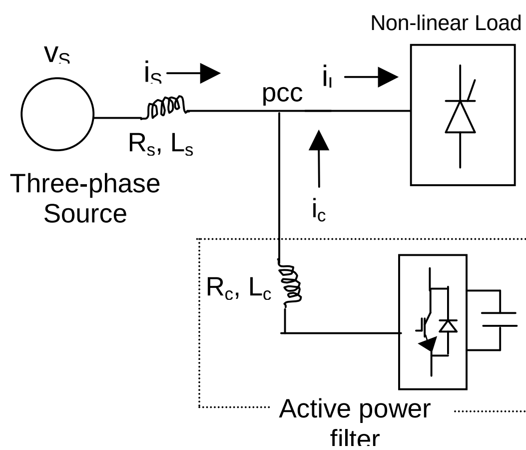

Fig. 1 Basic compensation principle of SAPF

2 Instantaneous active and reactive power p-q method [1]

Most active filters are designed based on the instantaneous active and reactive power p-q theory. The active filter reference currents

(i_{ca}^{*}, i_{cb}^{*}, i_{cc}^{*}) are obtained from the instantaneous active and reactive powers p_L and q_L of the non-linear load. This is achieved by transforming the mains voltage and load current into two-axis α-β co-ordinates by (1) and (2).

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{2/3} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3/2} & -\sqrt{3/2} \end{bmatrix} \cdot \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} \quad \ldots (1)$$

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{2/3} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad \ldots (2)$$

The instantaneous active and reactive powers p_L and q_L are expressed as

$$\begin{bmatrix} p_L \\ q_L \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \quad \ldots (3)$$

The instantaneous active and reactive powers can be decomposed into oscillatory and average terms as $p_L = p_L = \tilde{p}_L + P_L$ and $q_L = \tilde{q}_L + Q_L$. Under balanced and sinusoidal mains voltage conditions, the average power components are related to the fundamental current and the oscillatory components represent all higher order current harmonics. After eliminating the average power components by low-pass filter (LPF), the powers to be compensated are $p_c = -\tilde{p}_L$ and $q_c = -\tilde{q}_L$. The reference compensation currents are obtained by inverting the matrix in (3). These currents can be calculated by (4) and (5).

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \cdot \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \cdot \begin{bmatrix} p_c \\ q_c \end{bmatrix} \quad \ldots (4)$$

$$\begin{bmatrix} i_{ca}^{*} \\ i_{cb}^{*} \\ i_{cc}^{*} \end{bmatrix} = \sqrt{2/3} \cdot \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3/2} \\ -1/2 & -\sqrt{3/2} \end{bmatrix} \cdot \begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} \quad \ldots (5)$$

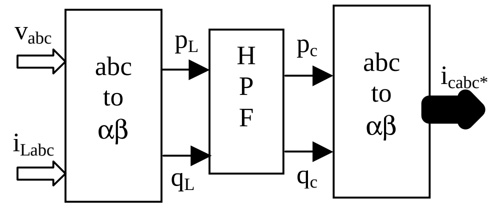

Fig. 2 Generation of reference compensating current by p-q method

3 Instantaneous power balance method [4]

The conventional instantaneous active and reactive power p-q theory needs coordinate transformations (a-b-c to α-β and vice versa). In this method, the compensating current is determined based on the balance of the instantaneous active and reactive power generated in the SAPF. The three phase instantaneous active power consumed by the load is

$$p_L = v_a\, i_{La} + v_b\, i_{Lb}(t) + v_c\, i_{Lc} \quad \ldots (6)$$

The three phase instantaneous reactive power in each phase becomes

$$q_{La} = v_b\, i_{Lc} - v_c\, i_{Lb}$$
$$q_{La} = v_c\, i_{La} - v_a\, i_{Lc}$$
$$q_{La} = v_a\, i_{Lb} - v_b\, i_{La} \quad \ldots (7)$$

The instantaneous active and reactive power delivered to a nonlinear load must satisfy (8) and (9).

$$p_L = p_s + p_c = p_{L1} + p_{Lh} \quad \ldots (8)$$
$$q_{fk} = q_{Lk},\ k = a,b,c \quad \ldots (9)$$

where p_s - instantaneous active power supplied by the source

p_f -instantaneous active power supplied by the SAPF

p_{L1} - instantaneous active fundamental power of the load

p_{Lh} - instantaneous harmonic power of the load

q_{Lk} - instantaneous reactive power generated by the SAPF at phase k.

In order to ensure that the fundamental active power is supplied to the load from the source, the instantaneous reactive power and harmonic power must be compensated by the SAPF. When considering the compensation of both harmonic and reactive power, p_f is expressed as

$$p_c = v_a\, i_{ca} + v_b i_{cb} + v_c i_{cc} = p_{Lh} \quad \ldots (10)$$

From (9) and (10), the reference compensating currents are determined as:

$$i_{ck} = i_{Lk} - \frac{p_{L1}}{v_a^2 + v_b^2 + v_c^2} v_k \text{ , } k = a, b, c \quad ...(11)$$

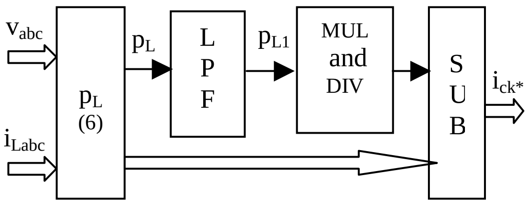

Fig. 3 Generation of reference compensating current by power balance method

4 Instantaneous active and reactive current component i_d-i_q method [3]

In this method, the reference compensating currents i_c^* are obtained from the instantaneous active and reactive current components i_{Ld} and i_{Lq} of the non-linear loads. The supply voltages and the load current in a-b-c coordinates are transformed to into two-axis α-β co-ordinates by (12) and (13). The dq load current components are derived from a synchronous reference frame based on the Park transformation, where θ represents the instantaneous voltage vector angle.

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \quad \text{…(12)}$$

$$\theta = \tan^{-1}(v_\alpha / v_\beta) \quad \text{…(13)}$$

Under balanced and sinusoidal supply voltage conditions, angle θ is a uniformly increasing function of time. This transformation angle is sensitive to voltage harmonics and unbalance. Using (12) in (13) we obtain

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \frac{1}{\sqrt{v_\alpha^2 + v_\beta^2}} \cdot \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \quad (14)$$

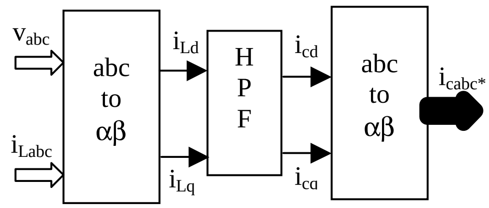

Fig. 4 Generation of reference-compensating current by i_d-i_q method

The instantaneous active and reactive components of the load currents can be decomposed into oscillatory and average terms as: $i_{Ld} = \tilde{i}_{Ld} + I_{Ld}$ and $I_{Lq} = \tilde{i}_{Lq} + I_{Lq}$. The fundamental current, which constitutes the average current component, is eliminated from the all-higher order harmonic component (oscillatory component) using a low-pass filter. The currents to be compensated are $i_{cd} = -\tilde{i}_{cd}$ and $i_{cq} = \tilde{i}_{cq}$. The compensation currents in two-axis α-β co-ordinates is obtained from (15).

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{\sqrt{v_\alpha^2 + v_\beta^2}} \cdot \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_{cd} \\ i_{cq} \end{bmatrix} \quad (15)$$

The reference compensation currents in a-b-c co-ordinates are obtained from (16).

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = \sqrt{2/3} \cdot \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3/2} \\ -1/2 & -\sqrt{3/2} \end{bmatrix} \cdot \begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} \quad \text{…(16)}$$

5 Fourier series method [5]

In this method, the reference-compensating current is obtained from the fundamental component of the load current. According to Fourier series, the instantaneous periodical load current $i_L(t)$ can be expressed as

$$i_L(t) = \sum_{n=1}^{N} \sqrt{2}\, I_{Ln} \sin(n\omega t + \phi_n)$$

$$= \sqrt{2}\, I_{L1} \cos\phi_1.\sin(\omega t) + \sqrt{2}\, I_{L1} \sin\phi_1.\cos(\omega t) + \sum_{n=2}^{N} \sqrt{2}\, I_{Ln} \sin(n\omega t + \phi_n) \quad \ldots(17)$$

where

$\omega = 2\pi f$ – fundamental angular frequency

I_{Ln} - rms value of the nth harmonic current

ϕ_n - phase angle of the nth harmonic current

The load current has three components namely

$$i_L(t) = i_{Lp}(t) + i_{Lq}(t) + i_{Lh}(t) \quad \ldots(18)$$

where $i_{Lp}(t) = \sqrt{2}\, I_{L1} \cos(\phi_1).\sin(\omega t)$ - active fundamental component ...(19)

$i_{Lq}(t) = \sqrt{2}\, I_{L1} \sin(\phi_1).\cos(\omega t)$ - reactive fundamental component

$i_{Lh}(t) = \sum_{n=2}^{N} \sqrt{2}\, I_{Ln} \sin(n\omega t + \phi_n)$ - harmonic component

Multiplying (17) with sinωt and integrating between zero and T gives

$$\int_0^T i_L(t).\sin(\omega t).dt = \int_0^T \sqrt{2}\, I_{L1} .\cos(\phi_1).\sin^2(\omega t)\, dt$$

$$= T/2.\ \sqrt{2}\, I_{L1} \cos(\phi_1) \quad \ldots(20)$$

Substituting (20) into (19), the active fundamental component of load current becomes

$$i_{Lp}(t) = \left[\frac{2}{T}\int_0^T i_L(t).\sin(\omega t)\, dt\right] \sin(\omega t) \quad \ldots(21)$$

The reference current of active power filter can be easily obtained by subtracting the load current from its active fundamental component.

$$i_c^*(t) = i_L(t) - i_{Lp}(t) \quad \ldots(22)$$

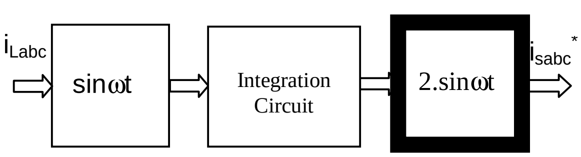

Fig. 5 Generation of reference source current by Fourier series method

6 DC link voltage regulation method [2, 6]

In this method, peak value of the reference source current is obtained by regulating the dc side capacitor voltage of the PWM inverter. This capacitor voltage is compared with a reference value and the error is processed in a PI controller. The reference source current is obtained by multiplying this peak value with the unit sine vectors that are in-phase with the supply voltage.

If non-linear load is applied, then the load current will have fundamental, reactive and harmonic components, which can be represented as

$$i_L(t) = \sum_{n=1}^{\infty} I_{Ln} .\sin(n\omega t + \phi_n) \quad \ldots(23)$$

$$= I_{L1}.\sin(\omega t + \phi_1) + \sum_{n=2}^{\infty} I_{Ln} .\sin(n\omega t + \phi_n)$$

The instantaneous load power can be given as

$$p_L(t) = v_s(t)\ .\ i_L(t)$$

$$= V_m I_{L1} \cos(\phi_1).\sin^2(\omega t) + V_m I_{L1} \sin(\phi_1).\sin(\omega t).\cos(\omega t) + V_m \sin(\omega t). \sum_{n=2}^{\infty} I_{Ln} \sin(n\omega t + \phi_n)$$

$$= p_f(t) + p_r(t) + p_h(t) \quad \ldots(24)$$

From (24), real power drawn by the load

$$p_f(t) = V_m I_{L1} \cos(\phi_1).\mathrm{Sin}^2(\omega t) = v_s(t).i_s(t) \ldots(25)$$

From (25), source supplied by the source after compensation is

$$i_s(t) = p_f(t)/\ v_s(t) = I_{L1} \cos(\phi_1)\ .\ \mathrm{Sin}\ (\omega t)$$

$$= I_{sm} \sin(\omega t)$$

where, $I_{sm} = I_{L1} \cos(\phi_1)$ ...(26)

The utility has to supply for the capacitor leakage and inverter switching losses in addition to the real power of the load. Hence, total peak current supplied by the source is expressed as

$$I_{sp} = I_{sm} + I_{sL} \quad \ldots(27)$$

The reference source current is given by

$$i_s^*(t) = I_{sp}.\ \sin(\omega t) \quad \ldots(28)$$

This peak value of the reference source current has been estimated by regulating the dc side capacitor voltage of the PWM inverter. The reference compensating current is obtained as

$$i_c^*(t) = i_L(t) - i_s^*(t) \quad \ldots(29)$$

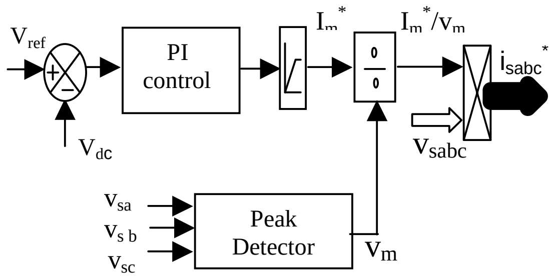

Fig.6 Generation of reference source current by DC link voltage regulation method

7 ComparativeAnalysis

The performance of different methods is investigated based on %THD of the source current after compensation under ideal (balanced and sinusoidal), non-ideal (un-balanced and distorted) supply voltage conditions and at different load conditions.

7.1 Ideal mains voltage

The balanced and sinusoidal three-phase mains voltages considered for simulation are

$$v_a = 230 \sin(\omega t)$$
$$v_b = 230 \sin(\omega t - 120^\circ)$$
$$v_c = 230 \sin(\omega t + 120^\circ) \quad ...(30)$$

From Fig. 7, it is observed that for all the five methods, THD of the source current is reduced well below 5% and meets IEEE-519 standards for the firing angle $\alpha = 0°$ and $30°$. When $\alpha = 60°$, THD exceeds the limits for pq theory, i_d-i_q method and power balance method.

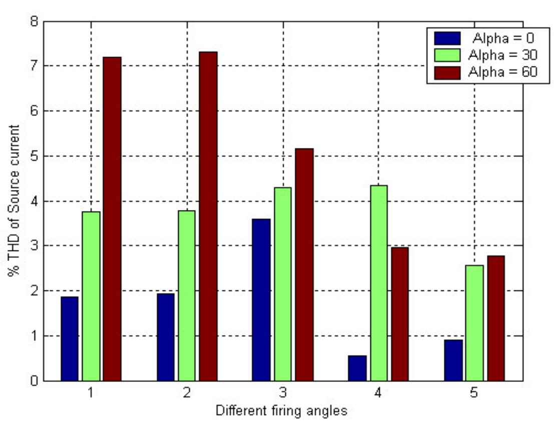

Fig.7 Comparative plots for five methods under balanced mains voltage and at different load conditions

7.2 Unbalanced mains voltage

The three-phase unbalanced and sinusoidal mains voltage considered for simulation is

$$v_a = 180 \sin(\omega t + 20^\circ)$$
$$v_b = 200 \sin(\omega t - 120^\circ)$$
$$v_c = 230 \sin(\omega t + 120^\circ) \quad ...(31)$$

Under unbalanced mains voltage, THD of the source current is reduced well below 5% for Fourier series method and DC link Voltage regulation method (Table 1). The performance of pq theory, power balance method and i_d-i_q method deteriorates.

The unbalanced three-phase mains voltage can be decomposed into positive and negative sequence components. Even in the two-axis co-ordinates, the mains voltages contain positive and negative sequence components. Hence, the sum of v_α^2 and v_β^2 will not be a constant. A second order and third order harmonic is observed in the compensated source current, where its amplitude depends on the negative sequence components. This leads to the degradation of the performance of pq method and i_d-i_q method.

Fig.8 shows unbalanced mains voltage (v_{abc}), load current (i_{Labc}), source current (i_{Sabc}) for pq method, Instantaneous Power Balance method, Instantaneous Active and Reactive current component i_d-i_q method, Fourier series method and DC link Voltage regulation method respectively. It is observed that the source current is sinusoidal and balanced for Fourier series and DC link Voltage regulation method.

7. 3 Distorted mains voltage

The following distorted three-phase mains voltage is considered for the simulation.

$$v_a = 230 \sin(\omega t) + 25 \sin(5\omega t)$$
$$v_b = 230 \sin(\omega t - 120^\circ) + 25 \sin(5\omega t - 120^\circ)$$
$$v_c = 230 \sin(\omega t + 120^\circ) + 25\sin(5\omega t + 120^\circ) \ldots(32)$$

Under distorted mains voltage, the performance of pq theory, power balance method and i_d-i_q method deteriorates. When the three-phase mains voltage is distorted, it can be decomposed as fundamental and harmonic components. The mains voltages in

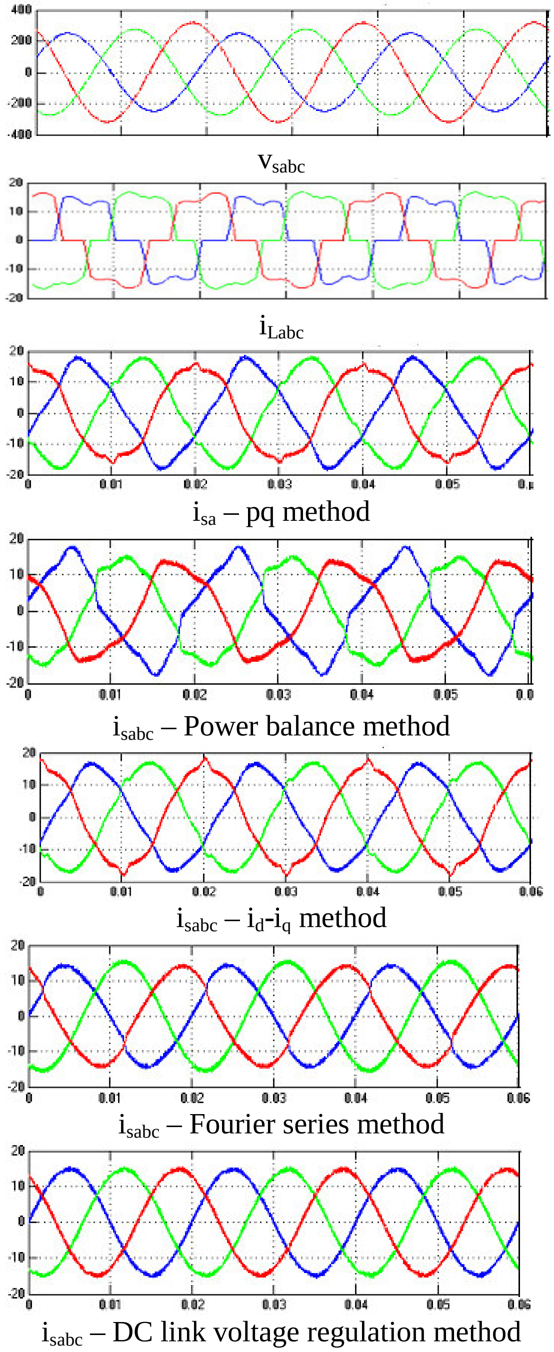

Fig.8 Unbalanced mains voltage, Load current and Source current for different methods

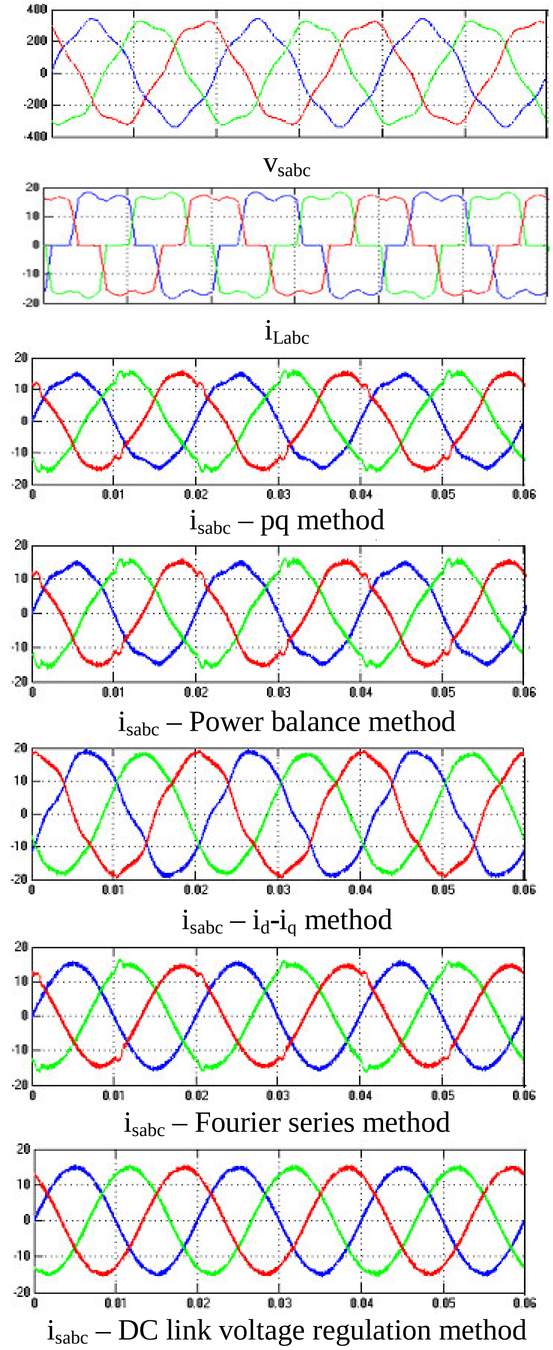

Fig.9 Distorted mains voltage, Load current and Source current for different methods

the two-axis system contain the fundamental and harmonic components. As the sum of v_α^2 and v_β^2 will not be a constant, $(k-1)^{th}$ and/or $(k+1)^{th}$ order harmonic is observed in the compensated source current. This factor leads to the degradation of performance of p-q, power balance method and id-iq method.

From (22) and (29), it is observed that the reference compensating current is independent of the mains voltage for Fourier series method and DC link voltage regulation method respectively. Hence, these two methods provide a good performance by maintaining THD of the source current at a

Reference compensating current estimation Techniques	% THD of source current for different load conditions under unbalanced supply voltage			% THD of source current for different load conditions under distorted supply voltage			No. of Multiplier / summer circuits	No. of current / Voltage sensors
	α=0°	α=30°	α=60°	α=0°	α=30°	α=60°		
% THD in source current before compensation	25.68	34.25	53.60	18.50	29.03	43.11		
Instantaneous p-q method	9.24	10.46	14.04	6.49	6.54	9.91	11/19	3/3
Power balance method	16.49	16.19	17.71	6.47	6.45	9.94	7/7	3/3
Instantaneous i_d-i_q method	6.48	6.57	9.42	6.54	7.48	7.16	12/15	3/3
Fourier series method	1.82	1.06	3.04	0.68	1.20	3.92	4/3	3/0
DC link voltage regulation method	1.05	1.58	3.07	1.81	2.60	3.69	2/4	3/1

Table 1 Comparison of different methods

value less than 5%. As the design of PI controller is simple and easy, DC link voltage regulation method is best suited for the compensation of harmonic and reactive power. Fig.10 shows its load perturbation response. The steady is reached after a delay of one cycle.

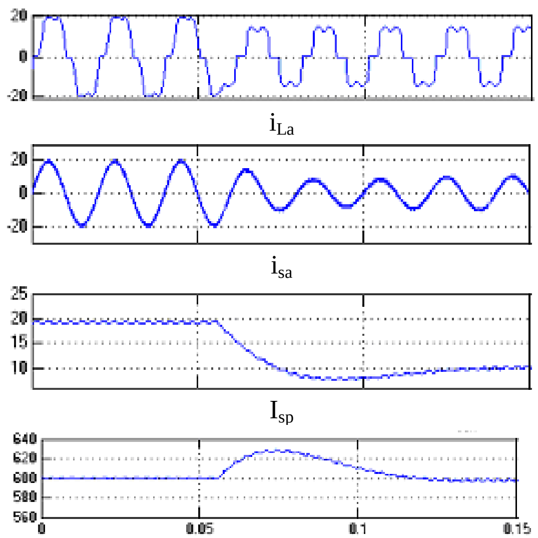

Fig.10 Load perturbation response

8 Conclusion

The performance of different reference compensating current estimation techniques is compared and investigated under ideal (balanced and sinusoidal), non-ideal (un-balanced and distorted) supply voltage conditions and at different load conditions.

Fourier series method and DC link voltage regulation method provides a good performance even under non-ideal (un-balanced and distorted) mains voltage conditions.

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