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A Novel Reference Current Generation Algorithm for Harmonic and Reactive Power Compensation in Non Ideal Three-phase Systems

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Abstract

Modern power system networks use active power filters for compensation of harmonic currents generated by non linear loads. In this paper a new method for generating reference currents for harmonic and reactive power compensation is proposed. The proposed method has the advantage that it generates the reference currents irrespective of the supply voltage and load conditions. So the source has to deliver only fundamental positive sequence active component of the load current even when the source voltage is distorted or unbalanced. This method also ensures that the source currents after compensation are balanced and at unity power factor. Simulation results and the comparative evaluation for different load and supply voltage conditions presented in this paper confirm the validity and practicability of the proposed method.

Keywords: Active power filters, id-iq method, power quality, reactive power compensation.

Introduction

The modern distribution systems are polluted due to the extensive use of power electronic devices such as uninterrupted power supplies, motor drives etc. These non linear loads draw non sinusoidal current from the source and causes voltage distortion at the point of common coupling (PCC). Other devices that are connected to the PCC are affected by the voltage distortion and hence suitable harmonic compensation is to be provided to maintain power quality. Nowadays active power filters (APFs) are used together with the non linear loads for the compensation of harmonics and reactive power.

In four wire distribution systems, unbalanced loading, harmonics and huge reactive power requirement are common and hence suitable compensation have to be provided. Akagi et.al in 1984 proposed the first compensator which can compensate for the harmonics and reactive power. They assumed a balanced three phase system with sinusoidal voltages and the theory proposed by Akagi is well known as the instantaneous reactive power theory [1, 2]. Several modifications were added to the theory incorporating three phase four wire systems and zero sequence components [3 – 6]. In [7] sinusoidal source current strategy was introduced considering the unbalanced and distorted system voltages. The unity power factor compensation strategy for APFs in [8] corrects the line currents so that the source currents fit to the voltage wave form in phase and shape. The APF control strategy employing decomposition of currents using the rotating coordinate transformation into active and reactive components is presented in [9] and [10]. Instantaneous active and reactive current component method (id-iq method) presented in [10], also called as synchronous reference frame method uses the mains voltages for deriving the rotating frame for the transformation and hence results in poor compensation under non ideal source voltages. Several researchers have contributed different methods for incorporating non ideal mains voltage conditions [11- 21] in APF control strategies. Other approaches like optimization [17], neural network etc. are also introduced in the control of APFs. The APF control strategy generates proper reference currents for harmonics and reactive power compensation. It has two control loops viz. the current control loop and the voltage control loop. The current control loop generates proper switching signals for the filter converter so that it tracks accurately the reference currents for compensation. The dc bus voltage of the converter is controlled by the voltage control loop and is maintained at the reference dc voltage. In this paper a new method for generating current reference for compensating unbalanced loading, reactive power and harmonics in three-phase four-wire system is presented. Figure 1 shows the schematic representation of three-phase four-wire APF connected to the four wire system feeding a non linear load. The split capacitor converter topology for four-wire APF is considered here and hysteresis band controller is used for the current control. The method presented performs well even when the mains voltages are unbalanced and/or distorted. Digital simulation results presented in this paper confirm the validity and practicability of the method.

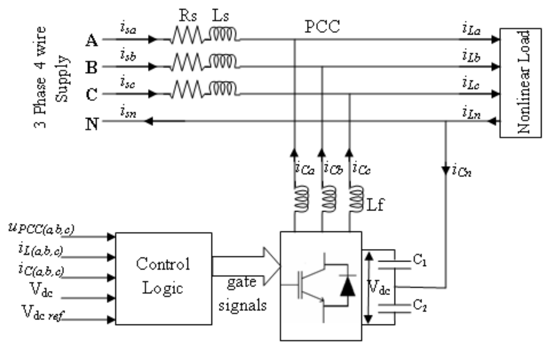


Fig. 1. Schematic representation of three-phase four-wire APF connected to the four wire system feeding a non linear load.

A review of the basic id-iq control strategy is given in section II as it is used as frame work for the proposed control method. Section III describes the proposed control method. Simulation results and comparative evaluation of the new method with id-iq control strategy are presented in section IV and the effectiveness of the new method is established. The paper is concluded in section V.

Instantaneous Active and Reactive Current Component Method

The instantaneous active and reactive current component method (id-iq method) for APF is aimed at compensating the harmonics and unbalance [9], [10], [20]. The id-iq control method is based on a synchronous reference frame ($dq0$ frame) derived from the mains voltage. The compensating currents are obtained from the instantaneous active and reactive current components in the $dq0$ frame. The reference currents for compensation are derived as follows.

The set of instantaneous phase voltages (u_a, u_b, u_c) and instantaneous currents (i_a, i_b, i_c) at PCC for three phase four wire system is first transformed to the stationary reference frame ($\alpha\beta 0$ frame) using the Clarke transformation by (1).

$$\begin{bmatrix} u_o \\ u_\alpha \\ u_\beta \end{bmatrix} = C \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} ; \begin{bmatrix} i_o \\ i_\alpha \\ i_\beta \end{bmatrix} = C \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{1}$$

where

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

For load current i_L, its components in the $dq0$ frame are obtained using the Park transformation using (2) where angle θ is the reference angle with respect to the $\alpha\beta 0$ frame.

$$\begin{bmatrix} i_{Lo} \\ i_{Ld} \\ i_{Lq} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{Lo} \\ i_{L\alpha} \\ i_{L\beta} \end{bmatrix}, \quad \theta = \tan^{-1}\left(\frac{u_\beta}{u_\alpha}\right) \tag{2}$$

As the zero sequence component is invariant by transformation, (2) can be written as

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \tag{3}$$

By geometrical relations [10], (3) can be rewritten as

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \frac{1}{\sqrt{u_\alpha^2 + u_\beta^2}} \begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \tag{4}$$

The active current i_{Ld} and reactive current i_{Lq} in the *dq0* frame are then decomposed into average and oscillatory components.

$$i_{Ld} = \bar{i}_{Ld} + \tilde{i}_{Ld} \quad , \quad i_{Lq} = \bar{i}_{Lq} + \tilde{i}_{Lq} \tag{5}$$

In id-iq method, the reference currents are generated for compensating $\tilde{i}_{Ld}$, i_{Lq} and zero sequence component i_{Lo} of load current so that the source delivers only the $\bar{i}_{Ld}$ component [9], [20]. And the reference source current in the $\alpha\beta o$ frame is given by;

$$i_{s\alpha\beta o}{}^{ref} = \bar{i}_{Ld} \frac{1}{\sqrt{u_\alpha{}^2 + u_\beta{}^2}} \begin{bmatrix} 0 \\ u_\alpha \\ u_\beta \end{bmatrix} \tag{6}$$

The reference currents in the *abc* coordinates can be calculated by using the inverse transformation of (1).

Proposed Method

In the proposed method, the control algorithm aims at making the compensated mains current purely sinusoidal and balanced, irrespective of the mains voltage condition and load characteristics. This is achieved by compensating the load current for harmonics and unbalance. Thus the mains current after compensation contain only the fundamental positive sequence component of the load current. The proposed method ensures reactive power compensation also so that the source currents after compensation are at unity power factor, i.e.; the compensated source currents will be in phase with the positive sequence voltage. Satisfying the above requirements this method includes a novel control algorithm for generating the reference currents for a shunt active filter, assuming three-phase four-wire system. This algorithm focuses on extracting the positive sequence load current component which forms the reference for compensated source current.

The uniqueness of the new method is that the load currents are transferred to a synchronously rotating frame locked to the positive sequence voltage. In this paper, this frame is denoted as $dq0^+$ frame. The frame is extracted from the mains voltage using a positive sequence voltage detector (PSVD) employing phase locked loop (PLL) [22]. The transformation angle θ^+ is obtained from the PSVD for transforming the currents to the $dq0^+$ frame. In this frame, the positive sequence current components appear as dc components. These dc components are filtered in the $dq0^+$ frame and transformed back to abc coordinates to form the source current reference.

(a) Positive sequence voltage detector

The PSVD is used to derive the transformation angle θ^+ with respect to the positive sequence component for transforming the load current from abc frame to dqo^+ frame. A simple, fast and robust three-phase PLL based PSVD is employed for generating θ^+. The basic configuration of PLL adopted here is shown in Fig. 2 [22]. The angle θ^+ is obtained by integrating a frequency command ω^*. If this frequency ω^* matches with the utility frequency, the voltages u_d and u_q appear as dc values when θ^+ is synchronized with the positive sequence voltage.

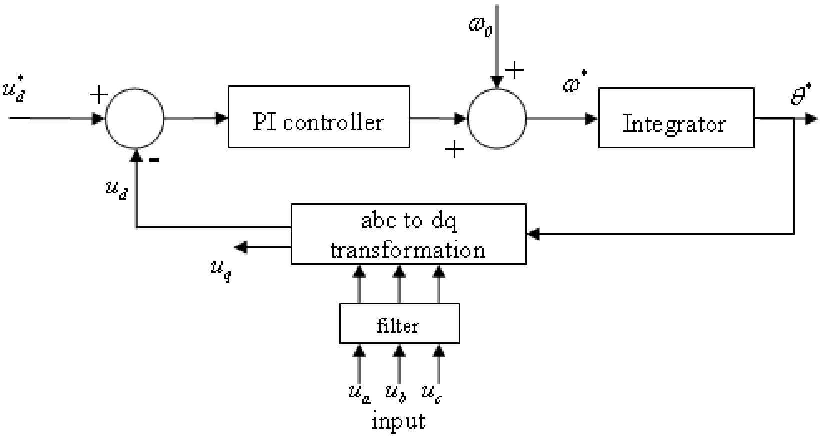


Fig. 2. Control block diagram of a PLL based PSVD

It should be noted that the voltage inputs to the PSVD may be unbalanced and/or distorted. So the performance of PLL will be deteriorated, since variation of utility angle with respect to time is not uniform. So in order to make the PLL immune to such disturbances the utility voltage inputs are pre-filtered using a fourth order Butterworth filter so that θ^+ perfectly locks to the positive sequence voltage component. The filter introduces a total phase lag of 2π radians. This will not affect the performance of PSVD since no quantitative information other than frequency and phase are extracted from the voltage inputs. Since the power system is a stiff one, it is assumed that any substantial changes that cannot be accommodated inherently by the PLL will not occur. Figure 3 shows the transient behavior of PSVD. It is seen that the PSVD locks perfectly with the positive sequence voltage.

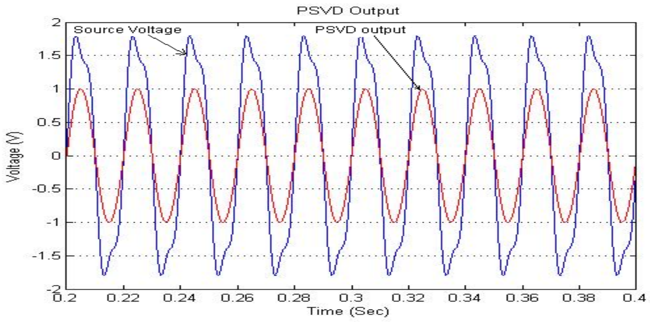


Fig.3. Output of PLL based PSVD.

(b) Reference Current generation

The proposed control algorithm focuses on generating the reference for compensated source current which is ensured to be balanced and sinusoidal and consequently the reference for harmonics, unbalanced loading and reactive power compensation is derived. Figure 4 shows the complete configuration of the proposed strategy. With the help of the PSVD, sine and cosine templates are derived and the current space vectors in abc frame are transformed to the synchronous positive sequence reference frame dqo^{+} using the Parks transformation. The transformation angle θ^{+} is a function of time and $\frac{d\theta^{+}}{dt}$ is a constant, provided the frequency remains constant. Any transient change in frequency will be adjusted by the PSVD and therefore the control strategy developed is inherently stable in generating the reference. Assuming three-phase four-wire system, the proposed control algorithm is formulated as follows.

The three phase load currents i_{La}, i_{Lb}, i_{Lc} are first transformed to the $\alpha\beta 0$ coordinates as $i_{L\alpha}, i_{L\beta}, i_{Lo}$ using (1). Then these currents are then transformed to the $dq0^{+}$ frame using the Parks transformation as,

$$\begin{bmatrix} i_{Lo} \\ i_{Ld+} \\ i_{Lq+} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta^{+} & \sin\theta^{+} \\ 0 & -\sin\theta^{+} & \cos\theta^{+} \end{bmatrix} \begin{bmatrix} i_{Lo} \\ i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \qquad (7)$$

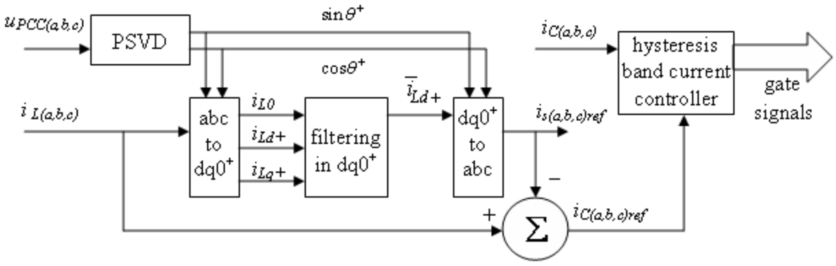


Fig. 4. Proposed Control Scheme

The transformation angle θ^{+} is derived using the PSVD.

The zero sequence component i_{Lo} is invariant under transformation and it is to be compensated fully.

The load current components in the dqo^{+} frame, i_{Ld+} and i_{Lq+} are decomposed into average and oscillatory components as,

$$i_{Ld+} = \bar{i}_{Ld} + \tilde{i}_{Ld} \tag{8}$$

$$i_{Lq+} = \bar{i}_{Lq} + \tilde{i}_{Lq} \tag{9}$$

The dc quantities $\bar{i}_{Ld}$ and $\bar{i}_{Lq}$ represent the fundamental positive sequence active and reactive components respectively of the load current. The oscillatory components $\tilde{i}_{Ld}$ and $\tilde{i}_{Lq}$ represent all higher order harmonic components including the first harmonic negative sequence current, as these components undergo a frequency shift in the spectra during transformation.

For compensating unbalance, harmonics and reactive power, the zero sequence component (i_{Lo}) and the oscillatory components ($\tilde{i}_{Ld}$, $\tilde{i}_{Lq}$) of the load current are to be compensated. So the reference for source current is generated first and hence filter current reference is obtained indirectly as shown in Fig. 4.

The source current reference in the $\alpha\beta 0$ coordinates can be computed as,

$$\begin{bmatrix} i_{Lo} \\ i^{+}_{L\alpha} \\ i^{+}_{L\beta} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta^{+} & -\sin\theta^{+} \\ 0 & \sin\theta^{+} & \cos\theta^{+} \end{bmatrix} \begin{bmatrix} 0 \\ \bar{i}_{Ld} \\ 0 \end{bmatrix} \tag{10}$$

Hence the positive sequence source current reference $i_{s\,abc^{ref}}$ is obtained as

$$\begin{bmatrix} i_{sa^{ref}} \\ i_{sb^{ref}} \\ i_{sc^{ref}} \end{bmatrix} = C^{T} \begin{bmatrix} i_{Lo} \\ i^{+}_{L\alpha} \\ i^{+}_{L\beta} \end{bmatrix} \tag{11}$$

So the filter current reference $i_{C\,abc^{ref}}$ can be obtained as

$$\begin{bmatrix} i_{Ca^{ref}} \\ i_{Cb^{ref}} \\ i_{Cc^{ref}} \end{bmatrix} = \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} - \begin{bmatrix} i_{sa^{ref}} \\ i_{sb^{ref}} \\ i_{sc^{ref}} \end{bmatrix} \tag{12}$$

From (10) and (11), it is clear that the reference source current contains only the positive sequence active current component. All the other load current components are compensated by the APF and therefore the source current after compensation becomes sinusoidal, balanced and at unity power factor.

Simulation Results and Comparative Evaluation

The proposed control algorithm for active power filter is implemented using MATLAB-Simulink to demonstrate the validity. Also a comparative evaluation is done with the id-iq control method to prove the effectiveness of the new algorithm. The simulation is performed assuming three-phase four-wire system where different source voltage and load conditions are considered. The parameters selected for simulation are shown in Table I.

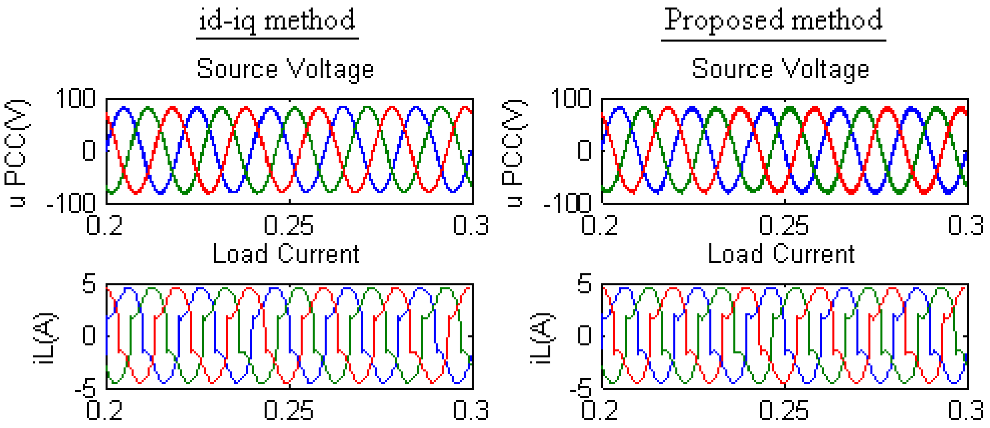
Table I : Simulation Parameters

Source	3 phase,100 V ph-ph, 50 Hz
Source Parameters	Rs=0.1Ω, Ls=0.1 H
Filter resistance and inductance	Rf=0.01Ω, Lf=5mH
Capacitor C1, C2	4000 microfarad
Initial Capacitor Voltage	125 V
Reference dc voltage	250 V
Hysteresis band (current control loop)	0.2
Voltage Control loop	Kp=0.4, Ki=15.4
Load	Bridge rectifier on each phase with R L load

Simulation is performed for four different conditions and the performance of id-iq method and the proposed method is compared in each case. The THD values shown along with the waveforms are the maximum values obtained in each case. The values obtained are detailed in the respective tables.

Case I: Balanced Source Voltage and Balanced Load Current

In case I balanced condition is selected for simulation. The results are shown in Fig. 5. It can be seen that both the methods perform well and the THD values are within the limits of power quality. The values are summarized in Table II. From Table II it can be read that the proposed method has better performance compared to id-iq method with respect to THD.



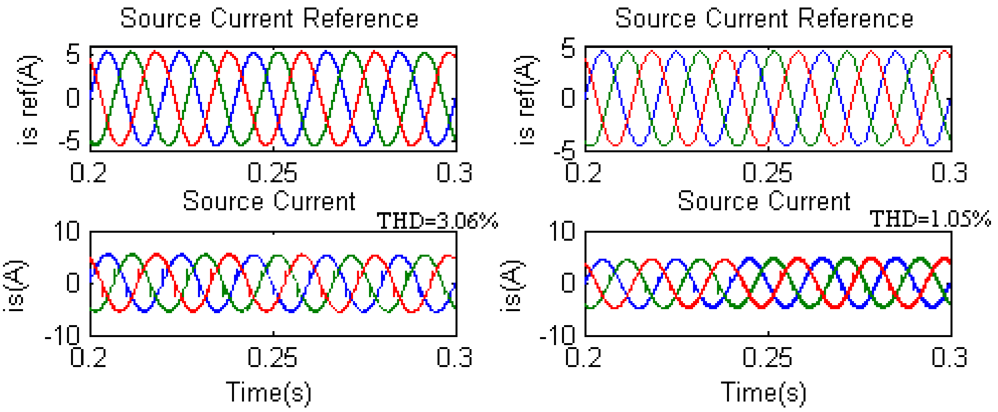


Fig. 5. Case I: Balanced Source Voltage and Balanced Load Current

Table II : Results Summary of Case I

Phase		Source Voltage		Load Current		Source Current	
		id-iq method	proposed method	id-iq method	proposed method	id-iq method	proposed method
A	Mag	81.11V	81.19V	4.682A	4.682A	5.417A	4.583A
	THD	0.08%	0.02%	21.78%	22.26%	3.06%	0.98%
B	Mag	81.11V	81.19V	4.682A	4.682A	5.419A	4.584A
	THD	0.08%	0.02%	21.79%	22.22%	3.06%	1.05%
C	Mag	81.11V	81.19V	4.682A	4.682A	5.418A	4.584A
	THD	0.08%	0.02%	21.79%	22.25%	3.11%	0.97%

Case II: Unbalanced Source Voltage and Balanced non linear load.

In this case an unbalanced source voltage is applied by injecting 0.1pu fundamental negative sequence along with the fundamental positive sequence voltage. The THD of source voltage remains almost same as in case I. In this case the APF has to compensate for harmonics and unbalance in the load currents. In Fig. 6, it is seen that the proposed method limits the THD where id-iq strategy cannot satisfy the standard. Moreover source current is also balanced using the new method. Table III gives the values in detail.

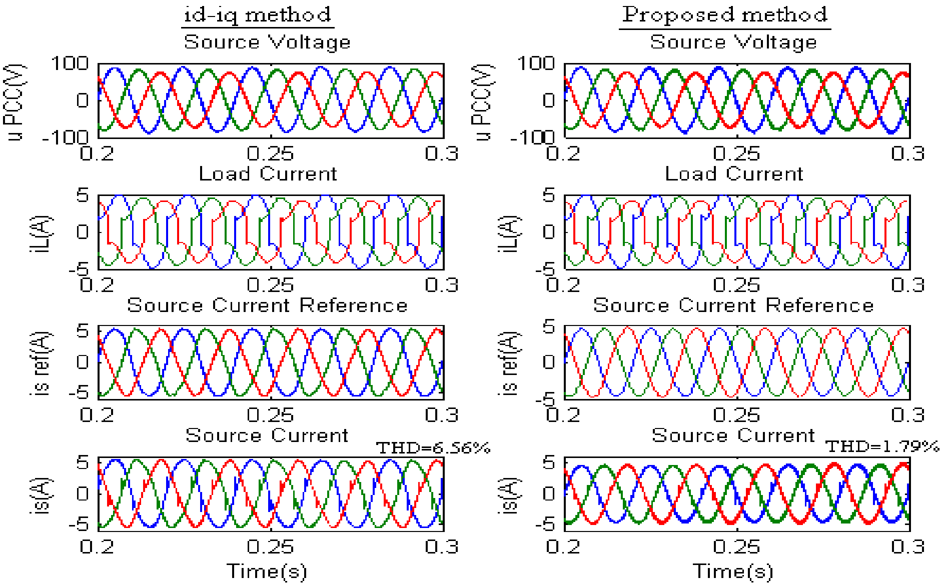


Fig. 6. Case II: Unbalanced Source Voltage and Balanced non linear load.

Table III : Results Summary of Case II

Phase		Source Voltage		Load Current		Source Current	
		id-iq method	proposed method	id-iq method	proposed method	id-iq method	proposed method
A	Mag	88.25V	88.34V	5.090A	5.096A	5.661A	4.636A
	THD	0.10%	0.03%	21.72%	22.12%	6.56%	1.79%
B	Mag	81.52V	81.62V	4.706A	4.706A	5.431A	4.572A
	THD	0.09%	0.02%	21.80%	22.26%	4.90%	1.15%
C	Mag	74.17V	74.22V	4.281A	4.280A	5.189A	4.688A
	THD	0.09%	0.02%	21.87%	22.24%	6.00%	1.32%

Case III: Unbalanced and distorted voltage; balanced non linear load.

In case III, an additional positive sequence fifth harmonic voltage is injected to the unbalanced voltage applied in case II. In this condition the reference current generated itself is distorted in the id-iq method which results in poor compensation. At the same time the proposed method works well in this condition also, because here, the reference currents are generated by using a decoupled $dq0^{+}$ reference frame using the PSVD. Hence the reference currents are purely sinusoidal. This is an added advantage of this method. The results are shown in Fig. 7 and Table IV.

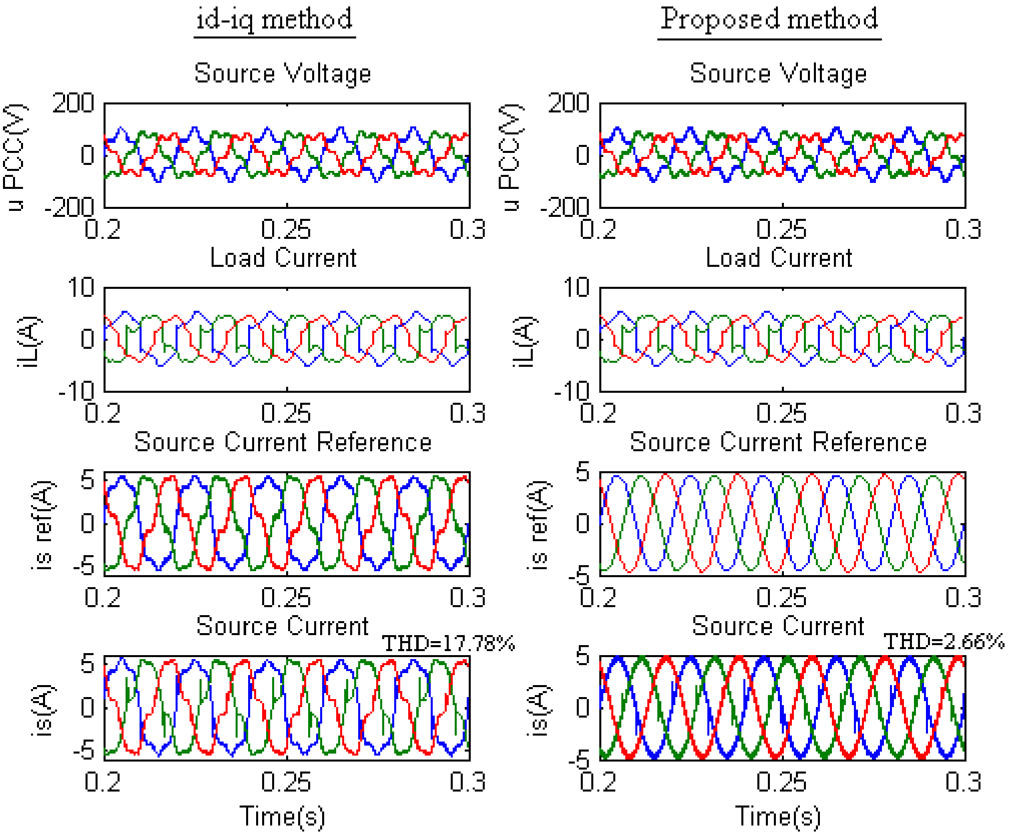


Fig. 7. Case III: Unbalanced and distorted voltage; balanced non linear load.

Table IV : Results Summary of Case III

Phase		Source Voltage		Load Current		Source Current	
		id-iq method	proposed method	id-iq method	proposed method	id-iq method	proposed method
A	Mag	88.24V	88.34V	5.162A	5.165A	5.682A	4.706A
	THD	18.46%	18.49%	25.19%	25.43%	17.78%	2.66%
B	Mag	81.54V	81.61V	4.528A	4.518A	5.288A	4.626A
	THD	19.95%	20.01%	33.54%	34.40%	15.99%	1.68%
C	Mag	74..17V	74.21V	4.349A	4.351A	5.138A	4.738%
	THD	21.93%	22.00%	13.68%	13.81%	15.41%	0.63%

Case IV: Balanced Source Voltage and Unbalanced non linear load.

Simulation results for case IV are presented in Fig. 8. and the values are tabulated in Table V. In this case an unbalanced non linear load is applied in both the methods. The load inductance is kept constant and load resistance in phase B is reduced. In this case the unbalance load currents and the harmonics have to be compensated. Here also, the proposed method shows better compensation.

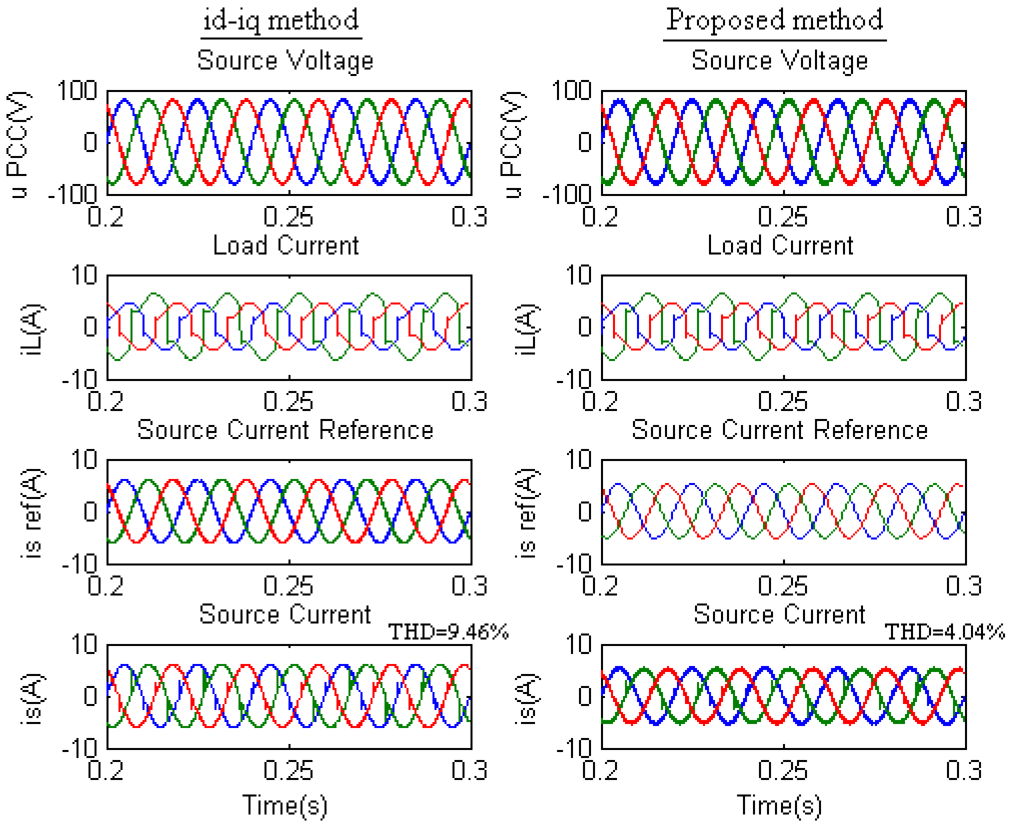


Fig. 8. Case IV: Balanced Source Voltage and Unbalanced non linear load

Table V : Results Summary of Case IV

Phase		Source Voltage		Load Current		Source Current	
		id-iq method	proposed method	id-iq method	proposed method	id-iq method	proposed method
A	Mag	81.05V	81.13V	4.679A	4.679A	6.031A	5.232A
	THD	0.09%	0.03%	21.77%	22.21%	2.94%	1.23%
B	Mag	81.05V	81.13V	6.556A	6.556A	6.05A	5.168A
	THD	0.27%	0.09%	28.75%	29.16%	9.46%	4.04%
C	Mag	81.05V	81.13V	4.679A	4.674A	6.028A	5.176%
	THD	0.08%	0.02%	21.77%	22.26%	2.85%	1.11%

Conclusion

A new reference current generation algorithm for harmonic and reactive power compensation using shunt active power filter is proposed in this paper. The proposed method ensures that the source current after compensation is balanced and sinusoidal at unity power factor. The uniqueness of this method is that it is immune to any supply voltage distortions and load characteristics, hence gives better results under varying system conditions. This control strategy has a bandwidth limitation due to the phase locked loop, implemented in the positive sequence detector. But it is assumed that any substantial changes in frequency that cannot be accommodated inherently by the phase locked loop will not occur as the power system is stiff. The proposed method is compared with the id-iq method and is observed that it performs well even in the conditions where the latter one results in poor compensation. The results obtained using the proposed method conforms to the IEEE-519 Standard. As this method uses the frame work of id-iq method, it can be called as 'modified id-iq method'. The simulation results presented confirms the effectiveness, validity and practicability of the proposed method.

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