An Optimization Based Algorithm for Shunt Active Filter Under Unbalanced and Nonsinusoidal Supply Voltages

Koteswara Rao U., Mahesh K. Mishra, *Member*, *IEEE* and Vincent G., *Student Member*, *IEEE*

***Abstract*—When the supply voltages are balanced and sinusoidal, load compensation can give both unity power factor (UPF) and perfect harmonic cancellation (PHC) source currents. But under distorted supply voltages, achieving both UPF and PHC currents are not possible and contradictory to each other. Hence there should be an optimal performance between these two important compensation goals. This paper presents an optimal control algorithm for load compensation under unbalanced and distorted supply voltages. In this algorithm source currents are compensated for reactive, imbalance components and harmonic distortions set by the limits. By satisfying the harmonic distortion limits and power balance, this algorithm gives the source currents which will provide the maximum achievable power factor. The detailed simulation results using MATLAB are presented to support the performance of the proposed optimal control algorithm.**

***Index Terms*-- Active power filter (APF), load compensation, optimization, perfect harmonic cancellation, unbalanced and distorted supply voltages, unity power factor.**

I. Introduction

THE increased use of static power converters such as single phase, three phase rectifiers and a large number of power electronics based equipments, generate considerable disturbance and pollution in the distribution power system. Single phasing operation and the three-phase unbalanced loads cause a significant amount of neutral current flow, which is undesirable. Due to unbalanced and nonlinear loads, the source currents drawn from the supply are unbalanced and distorted. These currents produce nonlinear voltage drops across the feeders, which result in the polluted voltages at the supply point of the utility [1]. Hence it is required to compensate the unbalance, harmonic and reactive component of the load currents under various supply voltage conditions. A simple solution to alleviate these problems is to use shunt connected active power filter (APF) at the appropriate location in the distribution system. The selection of control strategy for APF plays an important role to get desired compensation characteristics. From the literature survey, it is understood that the authors are using mainly two control strategies [2]-[10] to get the reference source currents. The first one is to get the perfect harmonic cancellation (PHC) [2]-[3], [5]-[7], [9]-[10] and the other one is to obtain unity power factor (UPF) [4]-[6], [8] at the source. However, both these strategies have their own advantages and disadvantages. The use of PHC strategy results in distortion-free source current and it is proved that under this strategy APF provides better performance [3]. However using this strategy, the power factor is not unity and it depends on the distortion of the supply voltage.

By implementing the UPF control strategy, the rms value of the source current can be minimized for the given average load power. The damping effect provided by the resistive part of the compensated load can be preserved in case of the resonance phenomena particularly in voltage distorted grids, otherwise severe voltage distortion results at the PCC [8]. The disadvantage of this strategy is that the source current after compensation resembles the supply voltages in unbalance and distortion. Hence the unbalance and distortion in the source currents are not compensated and wholly depend on the supply voltages. In literature [2]-[10], both the PHC and UPF control strategies have been realized by different approaches. In order to achieve the PHC, Aredes [3] and Rafiei [6] used the α-β positive sequence fundamental extraction in the compensation algorithm, which is computation intensive since at each instant transformations from *abc* to α-β and α-β to *abc* are required. In the above work, the calculation of average load power influences the dynamic response of the APF. Also the computation of instantaneous load reactive power in the α-β frame recently invited some critics [11].

In [7], authors achieved PHC based on the dc link dynamics of the voltage source inverter. The magnitude of the reference source current is generated from the feedback of dc storage capacitor voltage. The loss or gain of charge stored by the capacitor is an indication of the instantaneous power balance between the source and the total load including the losses in the inverters. Thus a negative feedback of the capacitor voltage can be utilized to adjust the magnitude of the desired source currents. However, the compensator dynamic response is slow because it uses the dc link voltage control as a means of reference currents generation.

In order to achieve unity power factor, Rafiei [6] uses the α-β transformation which is computation intensive as said earlier. In [5], [8] dc link dynamics has been employed to find out the conductance factor. After that, the desired source currents can be achieved by multiplying the conductance factor with the unity phase-locked supply voltages. But it is

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slow in response as it works on the basis of dc voltage control. As compared to control theories mentioned above, the application of instantaneous symmetrical component theory [12] is simple in formulation and devoid of ambiguous definitions of instantaneous reactive power too as in [2]. Using this theory, a new algorithm to achieve PHC, which uses the positive sequence fundamental of the distorted and unbalanced supply voltages, is proposed in [9]. When the supply voltages available are balanced and sinusoidal, the compensation for load current with unbalance, harmonics and reactive power (PHC strategy) results in unity power factor (UPF strategy) and compensation for UPF results in harmonic free source current (PHC). But when the supply voltages available are distorted, the compensation for PHC doesn't result in UPF and vice-versa [6]. Hence there should be an optimal performance between source current THD limits and unity power factor [6], [13-14].

An optimal and flexible control strategy is proposed in [6]. In this method, a two step process is adopted to get the desired source currents. First, the actual voltages are processed through the filters whose gains are optimized and tuned, to get the desired voltages. After that these voltages are multiplied by a constant to get the reference source currents which will give the average power equal to the load average power. The drawbacks of this method are: filters used to get the desired voltages and average load power deteriorates the dynamic performance of the compensator. Further it employs *p-q* theory which is not applicable for single phase systems and generates some additional harmonics in the extracted reference currents under distorted supply voltages [11].

In [13], authors used the non linear optimization technique to get the optimal performance between THD limits and UPF. This algorithm is not using *p-q* theory and it employs only one step process to get the reference source currents. However in this control algorithm, authors assumed that the supply voltages are balanced distorted only. As the presence of unbalance in the supply voltages is inevitable in the present power distribution system, this algorithm can not be used for such supply voltage conditions. In the above work, the compensator dynamic response is slow for fast changing loads with the method used for calculation of P_{lavg}. In present paper, a new control algorithm proposed for load compensation under unbalanced and distorted supply voltages. It uses the Fourier transform to get the balanced set of voltages from the unbalanced distorted supply voltages. For better dynamic response, moving average technique is adopted to calculate the P_{lavg}. After that, the desired source currents are computed by multiplying the balanced set of voltages with the conductance factors which are obtained from the optimization process. In the next section, the method of extraction of the balanced set of voltages from unbalanced distorted supply voltages using fourier transform is presented.

II. Extraction of the Balanced Set of Voltages from Unbalanced Distorted Supply Voltages

A schematic of three-phase, four-wire compensated system is shown in Fig. 1. The three-phase load may be unbalanced and nonlinear. The three-phase supply voltage may be unbalanced and distorted. A shunt APF (or compensator) and the load are connected at the point called the point of common coupling (PCC). For the sake of illustrating the concept, the compensator is considered to be ideal and it is comprised of three ideal current sources as shown in the figure.

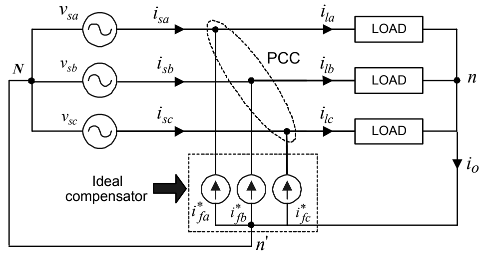

Fig. 1. A schematic of three-phase, four-wire compensated system.

Let the unbalanced and distorted voltages be represented by,

$$v_{sa}(t) = \sum_{n=1}^{k} V_{man} \sin(n\omega t + \phi_{van}) \tag{1a}$$

$$v_{sb}(t) = \sum_{n=1}^{k} V_{mbn} \sin(n\omega t + \phi_{vbn}) \tag{1b}$$

$$v_{sc}(t) = \sum_{n=1}^{k} V_{mcn} \sin(n\omega t + \phi_{vcn}) \tag{1c}$$

The subscript, '*s*' stands for supply, subscripts *a*, *b*, *c* for the three phase notation, '*m*' for maximum or peak value and '*n*' for the harmonic number. The term '*k*' is the upper number of harmonics considered in the phase voltages responsible for distorting the voltages.

Let us denote an instantaneous positive sequence voltage as $v_{sa}^{+}(t)$, instantaneous negative sequence voltage $v_{sa}^{-}(t)$ and instantaneous zero sequence voltage $v_{sa}^{0}(t)$ respectively for phase-*a*. These sequence voltages are expressed using symmetrical transformation as following.

$$\begin{bmatrix} \boldsymbol{v}_{sa}^{0}(t) \\ \boldsymbol{v}_{sa}^{+}(t) \\ \boldsymbol{v}_{sa}^{-}(t) \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} v_{sa}(t) \\ v_{sb}(t) \\ v_{sc}(t) \end{bmatrix} \tag{2}$$

Here '*a*' is a complex operator and its value is $e^{j2\pi/3}$. Similarly, we can resolve the instantaneous load currents into its instantaneous zero, positive, negative sequence components. The above sequence components are denoted by bold faced letters as they are complex quantities as a function of time. The zero sequence components are however not complex quantities, still represented by bold faced letters to maintain uniformity in equations. In a balanced distorted system, the harmonics of order $3n+1$, $3n+2$, $3n+3$ rotate with $(3n+1)\omega$, $(3n+2)\omega$, $(3n+3)\omega$ radian frequencies according to the positive, negative, zero sequences respectively [15]. For this case $\boldsymbol{v}_{sa}^{+}(t)$, $\boldsymbol{v}_{sa}^{-}(t)$ and $\boldsymbol{v}_{sa}^{0}(t)$ in (2) will have $3n+1$, $3n+2$ and $3n+3$ harmonics respectively. In the unbalanced distorted system $\boldsymbol{v}_{sa}^{+}(t)$, $\boldsymbol{v}_{sa}^{-}(t)$ and $\boldsymbol{v}_{sa}^{0}(t)$ have all harmonic orders. The balanced steady state voltage harmonic components can be determined by using the following expressions. For $3n+1$ harmonic order, it is written as following.

$$\boldsymbol{V}_{sa\,(3n+1)}^{+} = \frac{\sqrt{2}}{T}\int_{t_1}^{t_1+T} \boldsymbol{v}_{sa}^{+}(t)\, e^{-j((3n+1)\omega t-\pi/2)} \tag{3}$$

where n=0, 1,…, k. The term t_1 is an arbitrary instant and T is the time period of a cycle. The above integration is carried out using a moving average filter to have a fast response time. From the above expression $\left|\boldsymbol{V}_{sa\,(3n+1)}^{+}\right|$ and $\angle \boldsymbol{V}_{sa\,(3n+1)}^{+}$ can be obtained. The balanced 3n+2 harmonic voltages are given by

$$\boldsymbol{V}_{sa\,(3n+2)}^{-} = \frac{\sqrt{2}}{T}\int_{t_1}^{t_1+T} \boldsymbol{v}_{sa}^{-}(t)e^{-j((3n+2)\omega t-\pi/2)}. \tag{4}$$

where n=0, 1,…, k. From the above expression $\left|\boldsymbol{V}_{sa(3n+2)}^{-}\right|$ and $\angle \boldsymbol{V}_{sa(3n+2)}^{-}$ can be obtained. Similarly, the 3n+3 harmonic voltages are obtained as following.

$$\boldsymbol{V}_{sa\,(3n+3)}^{0} = \frac{\sqrt{2}}{T}\int_{t_1}^{t_1+T} \boldsymbol{v}_{sa}^{0}(t)e^{-j((3n+3)\omega t-\pi/2)}. \tag{5}$$

where n=0, 1,…, k. From the above expression $\left|\boldsymbol{V}_{sa(3n+3)}^{0}\right|$ and $\angle \boldsymbol{V}_{sa(3n+3)}^{0}$ can be calculated.

Therefore, the balanced quantities in the case of unbalanced and distorted supply voltages are:

$$\left.\begin{aligned}
v_{sa\,(3n+1)}^{+}(t) &= \sqrt{2}\left|\boldsymbol{V}_{sa\,(3n+1)}^{+}\right|\sin\left(3n+1\,(\omega t)+\angle \boldsymbol{V}_{sa\,(3n+1)}^{+}\right)\\
v_{sb\,(3n+1)}^{+}(t) &= \sqrt{2}\left|\boldsymbol{V}_{sa\,(3n+1)}^{+}\right|\sin\left(3n+1\,(\omega t-2\pi/3)+\angle \boldsymbol{V}_{sa\,(3n+1)}^{+}\right)\\
v_{sc\,(3n+1)}^{+}(t) &= \sqrt{2}\left|\boldsymbol{V}_{sa\,(3n+1)}^{+}\right|\sin\left(3n+1\,(\omega t+2\pi/3)+\angle \boldsymbol{V}_{sa\,(3n+1)}^{+}\right)
\end{aligned}\right\} 6)$$

$$\left.\begin{aligned}
v_{sa\,(3n+2)}^{-}(t) &= \sqrt{2}\left|\boldsymbol{V}_{sa\,(3n+2)}^{-}\right|\sin\left(3n+2\,(\omega t)+\angle \boldsymbol{V}_{sa\,(3n+2)}^{-}\right)\\
v_{sb\,(3n+2)}^{-}(t) &= \sqrt{2}\left|\boldsymbol{V}_{sa\,(3n+2)}^{-}\right|\sin\left(3n+2\,(\omega t-2\pi/3)+\angle \boldsymbol{V}_{sa\,(3n+2)}^{-}\right)\\
v_{sc\,(3n+2)}^{-}(t) &= \sqrt{2}\left|\boldsymbol{V}_{sa\,(3n+2)}^{-}\right|\sin\left(3n+2\,(\omega t+2\pi/3)+\angle \boldsymbol{V}_{sa\,(3n+2)}^{-}\right)
\end{aligned}\right\} (7)$$

$$\left.\begin{aligned}
v_{sa\,(3n+3)}^{0}(t) &= \sqrt{2}\left|\boldsymbol{V}_{sa\,(3n+3)}^{0}\right|\sin\left(3n+3\,(\omega t)+\angle \boldsymbol{V}_{sa\,(3n+3)}^{0}\right)\\
v_{sb\,(3n+3)}^{0}(t) &= \sqrt{2}\left|\boldsymbol{V}_{sa\,(3n+3)}^{0}\right|\sin\left(3n+3\,(\omega t-2\pi/3)+\angle \boldsymbol{V}_{sa\,(3n+3)}^{0}\right)\\
v_{sc\,(3n+3)}^{0}(t) &= \sqrt{2}\left|\boldsymbol{V}_{sa\,(3n+3)}^{0}\right|\sin\left(3n+3\,(\omega t+2\pi/3)+\angle \boldsymbol{V}_{sa\,(3n+3)}^{0}\right)
\end{aligned}\right\} (8)$$

where n=0,1,…, k in (6), (7) and (8). The three phase balanced set of voltages in the case of unbalanced and distorted supply voltages can be written as,

$$\begin{aligned}
v_{sa}^{'}(t) &= \sum_{n=0}^{k}\left(v_{sa(3n+1)}^{+}(t)+v_{sa(3n+2)}^{-}(t)+v_{sa(3n+3)}^{0}(t)\right)\\
v_{sb}^{'}(t) &= \sum_{n=0}^{k}\left(v_{sb(3n+1)}^{+}(t)+v_{sb(3n+2)}^{-}(t)+v_{sb(3n+3)}^{0}(t)\right).\\
v_{sc}^{'}(t) &= \sum_{n=0}^{k}\left(v_{sc(3n+1)}^{+}(t)+v_{sb(3n+2)}^{-}(t)+v_{sc(3n+3)}^{0}(t)\right)
\end{aligned} \tag{9}$$

Now $v_{sa}^{'}$, $v_{sb}^{'}$ and $v_{sc}^{'}$ form balanced quantities for the distorted and unbalanced supply voltages.

III. Optimization Technique to Get the Conductance Factors

In order to get the optimal performance between unity power factor and THD limits of source current, an optimization technique is employed as proposed in [14]. For achieving unity power factor, the source currents should be in phase and have the shape, harmonics same as the supply voltages. Then source currents have the unbalance and distortion same as that in the supply voltages. In order to make desired source currents as balanced, the balanced sets of voltages are multiplied by a conductance factors obtained from optimization technique, which will satisfy the power balance criterion and the distortion limits in the desired source current. The optimization process for phase-a is shown here. The balanced set of voltages for phase-a is rewritten for the sake of completeness as following.

$$v_{sa}^{'}(t) = \sum_{n=0}^{k}\left(v_{sa(3n+1)}^{+}(t)+v_{sa(3n+2)}^{-}(t)+v_{sa(3n+3)}^{0}(t)\right) \tag{10}$$

The desired source current for phase-a is given by

$$\begin{aligned}
i_{sa}^{'\,*}(t) &= k_1\left(v_{sa1}^{+}\right)\\
&+k_n\left(\sum_{n=1}^{k}\left(v_{sa(3n+1)}^{+}\right)+\sum_{n=0}^{k}\left(v_{sa(3n+2)}^{-}(t)+v_{sa(3n+3)}^{0}(t)\right)\right)
\end{aligned} \tag{11}$$

k_1 and k_n are the conductance factors for fundamental and other harmonics respectively. By controlling these factors, the THD in the current can be controlled. Lagrangian multiplier technique is used to get the conductance factors for the minimum apparent power by satisfying the mentioned constraints.

The general Lagrangian function is formed as shown below

$$L = f + \lambda\, r + \mu\, s. \tag{12}$$

where L is the Lagrangian function, f is the objective function, λ and μ are the Lagrangian multipliers and r and s are the equality and inequality constrains respectively. In the optimization technique the objective function is to minimize the apparent power which will directly influence on power factor correction. The equality and inequality constraints in the optimization process are, the desired source currents should supply the load average power and have THDs specified by the limits respectively. The Lagrange function is formulated as shown below [14].

$$\begin{aligned}
L &= \sum_{1}^{n}\left(V_{san}^{'}\right)^2\sum_{1}^{n}\left(I_{san}^{'}\right)^2+\lambda\left(\frac{P_{lavg}}{3}-\left(\left(V_{sa1}^{'}\right)^2k_1+\sum_{2}^{n}\left(V_{san}^{'}\right)^2k_n\right)\right)\\
&+\mu\left(\sum_{2}^{n}k_n^2\left(V_{san}^{'}\right)^2-I_{THD}^2k_1^2\left(V_{sa1}^{'}\right)^2\right)
\end{aligned} \tag{13}$$

In the above equation $V_{san}^{'}$ is the rms value of the n^{th} order balanced harmonic voltage component, $V_{sa1}^{'}$ is the rms value of the balanced fundamental, $I_{san}^{'}$ is the rms value of the n^{th} order balanced harmonic current component, I_{THD} is the harmonic limit on the source current and P_{lavg} is the average load power computed by the moving average filter to have the better dynamic response. It will take maximum period of one cycle if voltage and current have both odd and even harmonics. If the voltage and current have only odd harmonics, it will take half cycle only. The necessary conditions for constrained local minima of L are the first order derivatives with respect to the variables present in the function must be zero. Therefore

$$\frac{\partial L}{\partial k_1} = y_{\,1}\left[2k_1\left(x-I_{THD}^2\mu\right)-\lambda\right]=0 \tag{14}$$

$$\frac{\partial L}{\partial k_n} = y_n\left[2k_n\left(x+\mu\right)-\lambda\right]=0 \tag{15}$$

where $x = \sum_{1}^{n}\left(\left(V'_{san}\right)^2\right)$, $y_n = \left(V'_{san}\right)^2$.

$$\frac{\partial L}{\partial \lambda} = \frac{P_{lavg}}{3} - \left(\left(V'_{sa1}\right)^2 k_1 + \sum_{2}^{n}\left(V'_{san}\right)^2 k_n\right) = 0 \tag{16}$$

$$\frac{\partial L}{\partial \mu} = \sum_{2}^{n} k_n^2\left(V'_{san}\right)^2 - I_{THD}^2 k_1^2\left(V'_{sa1}\right)^2 = 0 \tag{17}$$

By solving (14)-(17), k_1 and k_n are obtained for an optimum power factor within acceptable THD limit of source current. These values are substituted in (11) to get the desired source current for phase-*a*. Similarly desired currents for other phases can be calculated with the same conductance factors. Therefore there is no need of performing optimization for other two phases as in [13]. This will reduce computation time of reference currents and ensure the average source power is equal to the average load power. After getting the desired source currents, the compensator currents for the three phases are obtained from the following equations

$$i'_{ca}{}^{*} = i_{la} - i'_{sa}{}^{*}\ ;\ i'_{cb}{}^{*} = i_{lb} - i'_{sb}{}^{*}\ ;\ i'_{cc}{}^{*} = i_{lc} - i'_{sc}{}^{*}. \tag{18}$$

These compensating currents are then realized by using the current controlled voltage source inverter (VSI) with hysteresis current control technique.

IV. Simulation Results With Ideal Compensator

In this section, detailed simulation studies for three-phase four wire system are presented to explain the PHC and UPF strategies along with the above discussed optimized control algorithm. The compensator is assumed to be ideal i.e., it has infinite bandwidth and no losses. The load considered is unbalanced and nonlinear. The unbalanced and distorted supply voltages taken for the study are given below.

$$\begin{aligned} v_{sa} &= 359.25\sin(\omega t) + 53.88\sin(2\omega t) + 35.92\sin(4\omega t) + \\ &\quad 32.33\sin(5\omega t) \\ v_{sb} &= 287.4\sin(\omega t - 120^0) + 43.11\sin(2\omega t - 240^0) + \\ &\quad 37.36\sin(4\omega t - 480^0) + 34.48\sin(5\omega t - 600^0) \\ v_{sc} &= 431.1\sin(\omega t + 120^0) + 53.88\sin(2\omega t + 240^0) + \\ &\quad 28\sin(4\omega t + 480^0) + 43.11\sin(5\omega t - 600^0) \end{aligned} \tag{19}$$

The supply voltages and the corresponding load currents are shown in Fig. 2 (a) and (b) respectively.

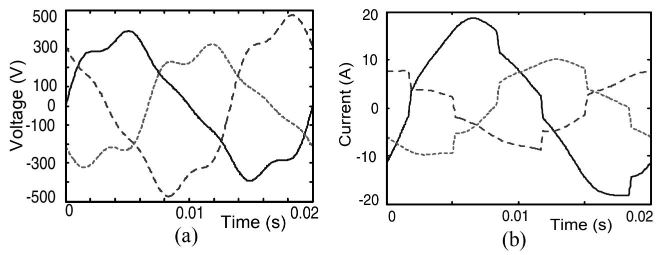

Fig. 2. (a) Supply voltages (b) Load currents

A. PHC Strategy

In this strategy, the fundamental positive sequence voltages are extracted from the supply. These voltages are then used to calculate reference source currents by using instantaneous symmetrical component theory [9]. The phase-*a* reference source current is expressed as following.

$$i_{sa1}^{+} = \frac{v_{sa1}^{+} - v_{sa1}^{0}}{\left(v_{sa1}^{+\,2} + v_{sb1}^{+\,2} + v_{sc1}^{+\,2} - 3\left(v_{sa1}^{0}\right)^2\right)} P_{lavg} \tag{20}$$

In the above equation v_{sa1}^{0} is the fundamental zero sequence voltage and its value is equal to zero as the considered supply voltages in (20) are fundamental positive sequence (balanced) voltages. Here the important aspect is that the term ($v_{sa1}^{+\,2} + v_{sb1}^{+\,2} + v_{sc1}^{+\,2}$) is constant at every instant. Hence, reference source currents resemble the fundamental positive sequence voltages with a scaling factor. Using this strategy, the compensated source currents become sinusoidal and balanced. The source and compensator currents are shown in Fig. 3 (a) and (b) respectively.

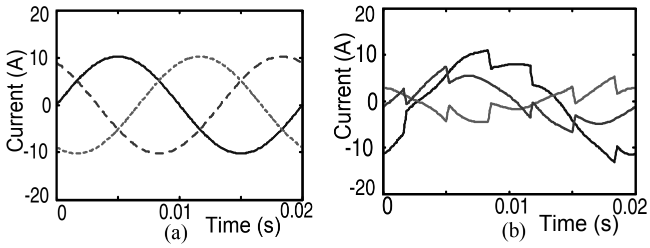

Fig. 3. (a) Source currents (b) Compensator currents

B. UPF Strategy

In this strategy, the denominator of (20) is replaced by mean value of sum of square of the supply voltages. Also the compensation for the zero sequence voltages is not provided; therefore v_{sa}^{0} term is eliminated in the numerator and denominator. As a consequence of this, the neutral current after compensation is no longer zero. The reference source currents are proportional to the actual supply voltages. For phase-*a*, source current is given below.

$$i_{sa} = \frac{v_{sa}}{\left\langle v_{sa}^2 + v_{sb}^2 + v_{sc}^2 \right\rangle} P_{lavg} \tag{21}$$

Here the symbol '$\langle\,\rangle$' represents running mean of ($v_{sa}^2 + v_{sb}^2 + v_{sc}^2$) over a period and its value is constant at every instant. The period of running mean is half or one cycle depending upon the odd or even harmonics in the supply voltages. In the above expression, P_{lavg} is also constant. Therefore, the source currents resemble the supply voltages. This operation results in UPF. If the mean of ($v_{sa}^2 + v_{sb}^2 + v_{sc}^2$) term is not considered, dissimilar harmonics will be present in voltages and currents and hence, UPF operation can not be achieved. The source and compensator currents for this strategy are shown in Fig. 4 (a) and (b) respectively.

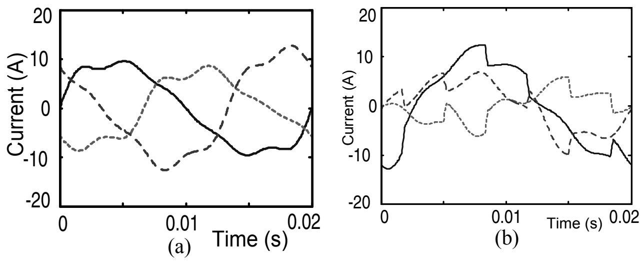

Fig. 4. (a) Source currents (b) Compensator currents

C. Optimization control algorithm with 5 % THD limit

The above mentioned optimized control algorithm which will give the optimal performance between the THD limit of source current and UPF is applied with THD limit of 5 %. The source and compensator currents for this method are shown below.

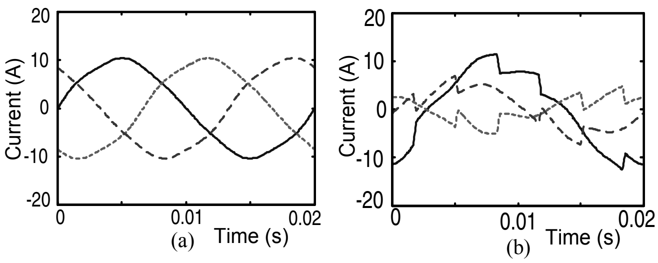

Fig. 5. (a) Source currents (b) Compensator currents

D. Optimization control algorithm with 10 % THD limit

The optimized control algorithm under the given unbalanced distorted supply voltages is performed by taking the constraints as, 10 % THD limit in source currents and the source has to supply only the load average power after compensation. Thus obtained source and compensator currents are shown below.

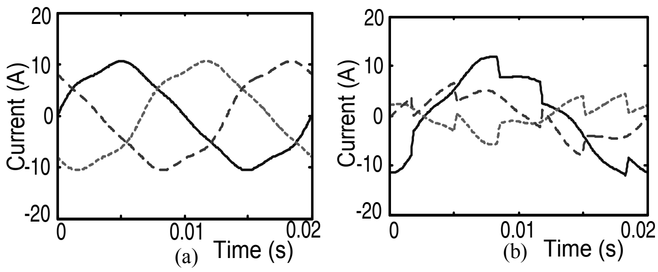

Fig. 6. (a) Source currents (b) Compensator currents

C. Optimization control algorithm with 17.26 % THD limit

The optimized control algorithm in this case is performed by taking the inequality constraint as 17.26 % THD limit in source currents and the equality constraint as source has to supply only the load average power after compensation. Thus obtained source and compensator currents are shown below. These currents shape is now close to same as supply voltages, which will ensure the power factor close to unity.

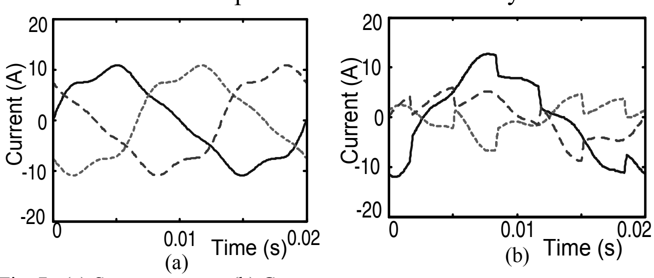

Fig. 7. (a) Source currents (b) Compensator currents

V. Analysis of the Simulation Results

For the simulation studies, the rms, THD values of supply voltages and rms, THD, and power factor values of the load currents are given in Table I. The performances of the five strategies under unbalanced and nonsinusoidal supply voltages are given Table II. Here NUPF, NPHC, O.C.A represent non unity power factor, non perfect harmonic cancellation and optimization control algorithm respectively.

PHC Strategy

In this strategy the source currents obtained are balanced and the THDs in the source currents are zero. The compensator rating for this strategy is minimum compared to the other strategies. But, power factor is not unity though the source currents are sinusoidal because of the harmonic component in supply voltages does not contribute to the average load power which in turn increases the apparent power. The value of the power factor wholly depends upon the supply voltage distortion

i.e. $pf = \frac{1}{\sqrt{1 + THD_v^2}}$ where THD_v is the total harmonic distortion of supply voltages.

UPF Strategy

Under this strategy the load damping effect is retained by shaping the source currents similar to the supply voltages, which will play important role in the case of resonance phenomena. The harmonic components which are similar in the supply voltages and source currents contribute to the average load power to make the power factor unity. The rms values of the source currents under this strategy are less, but the compensator rating is high compared to all other strategies. The other drawback of this strategy is that the distortion and unbalance in the currents are same as in the supply voltages.

Optimization control strategy

The above two control strategies, one compensates the current harmonics but does not provide unity power factor and the other gives unity power factor but cannot afford compensation of current harmonics and unbalance. Thus these are not fulfilling the aims of compensation. Hence an optimization control strategy is employed to get an optimal performance between UPF and PHC. In Table II the results of optimization algorithm is given for THD limit of 5 %, 10 % and 17.26 % in the source currents after compensation. First 5 % THD is allowed as per *IEEE*-519 standard. From the results it can be seen that the rms values of source currents are in between the UPF (minimum) and PHC (maximum) strategies by satisfying the standards of distortion current limit. The compensator rating and power factor is also optimized between UPF (maximum) and PHC (minimum). After that, 10 % THD limit was kept as a constraint to check the performance of the algorithm and the results are shown in Table II. Though reduction in rms values of source currents and increase in power factor values are favorable, the distortion limit in the source current is violating *IEEE*-519 standards and the compensator rating is increased. Next in order to achieve unity

TABLE I
SUPPLY VOLTAGE, LOAD CURRENT AND POWER FACTOR DATA

Supply Voltage rms (A)			Supply Voltage THD (%)			Load current Rms (A)			Load current THD (%)			power factor		
a	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*
259.13	208.62	309.23	20.14	23.19	17.26	12.83	7.04	5.46	10.75	14.03	15.97	0.835	0.916	0.833

TABLE II
RESULTS OF DIFFERENT STRATEGIES UNDER UNBALANCED AND DISTORTED SUPPLY VOLTAGES

Strategy	Source current rms (A)			Source current THD (%)			Source current peak (A)			Compensator current rms (A)			Power factor after compensation			Compensation characteristics
	a	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	
PHC	7.264	7.264	7.264	0.00	0.00	0.0	10.27	10.27	10.27	7.698	2.45	3.095	0.980	0.974	0.985	NUPF, PHC, balanced Fig. 3(a)
UPF	6.965	5.580	8.283	20.14	23.19	17.26	9.640	8.664	12.70	8.034	2.952	4.795	1.000	1.000	1.000	UPF, NPHC, unbalanced Fig. 4(a)
O.C.A 5 %	7.202	7.202	7.202	5.00	5.00	5.00	10.44	10.44	10.44	7.733	2.462	3.878	0.989	0.984	0.992	NUPF, NPHC, balanced Fig. 5(a)
O.C.A 10 %	7.159	7.159	7.159	10.00	10.00	10.00	10.60	10.60	10.60	7.785	2.526	3.886	0.995	0.991	0.997	NUPF, NPHC, balanced Fig.6(a)
O.C.A 17.26 %	7.129	7.129	7.129	17.26	17.26	17.26	10.83	10.83	10.83	7.886	2.699	3.954	0.999	0.998	1.000	NUPF, NPHC, balanced Fig. 7(a)

power factor from optimization control algorithm, the distortion limit in source current was kept as 17.26 %. From the table it can be observed that the power factor is unity in the phase-*c* as distortion in the source current and the supply voltage are same. In the other phases power factor is close to unity but not unity, because the distortion harmonics in source current and supply voltage are not same.

From the results of optimization control algorithm, by considering different distortion limits as constraints, it is learnt that by taking 5 % THD limit as constraint in the source, the algorithm gives the balanced source currents which are satisfying the *IEEE*-519 standards with the best power factor.

VI. CONCLUSION

The selection of the control strategy for APF has been found to influence the compensation characteristics. It was shown that, under distorted supply voltages any effort to increase the power factor results in increased THD of source currents and total compensation for current harmonics does not provide the unity power factor. In this paper, an optimal control algorithm is proposed to get a compromise between achieving unity power factor and THD current limits with compensation of reactive power and imbalance. The compensation characteristics of three control strategies i.e. PHC, UPF, optimization based algorithm are compared from the simulation results shown Table II. From the results it is clear that the proposed optimization technique renders the best possible compromise between the power factor and the harmonic distortion. The optimization algorithm to get conductance factors needs to be performed for only one phase, as the same factors can be used for the other two phases. This technique does not involve any transformation from one frame to another and it is not employing any low-pass filter (LPF) to get the average load power from the instantaneous power *P(t)*, which will deteriorate the dynamic performance of the compensator.

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