An Optimal and Flexible Control Strategy for Active Filtering and Power Factor Correction Under Non-Sinusoidal Line Voltages

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***Abstract*—This paper gives a new insight into the concept of load compensation under distorted voltages. Achieving both unity power factor (UPF) and perfect compensation of current harmonics are not possible where a competition will arise between these two important factors. Through evaluating the present control strategies, a generalized, optimal, and flexible control strategy (OFC) for harmonic compensation of utility lines is proposed. The proposed control strategy, which provides a unified and highly flexible compensation framework has the ability of programming for perfect current harmonics compensation, or (UPF) accomplishment, or other newly defined objectives such as maximizing the power-factor subject to some adjustable constraints on the level of current harmonics and unbalancing via an on-line optimization algorithm. The strategy can fulfill the IEEE-519 standards requirements, while guaranteeing the best achievable power factor and optimum required rating for the compensator. Theoretical concepts and practical features of the proposed control strategy have been shown through extensive simulation studies using MATLAB/SIMULINK programs.**

***Index Terms*—Active filter, distorted voltage, flexible compensation strategy, harmonics, optimization, power factor.**

I. INTRODUCTION

WIDESPREAD use of power electronic systems have increased harmonics in the utility power networks over the past three decades. Active power filters were developed for harmonic compensation and power factor correction [1], [2]. Fig. 1 shows the block diagram of a parallel active filter. In active filters, the compensation strategy is quite important and various strategies have been proposed to improve the performance of active filters [3]–[5], [7]–[12]. Regardless of compensating tools, decision about which components are undesirable is made based on the compensation strategy, especially where the voltages are nonsinusoidal [6], [13]–[15]. Generally, in the load compensation field we deal with the following two essential topics:

a) Aims of compensation: i.e., which components of the load current are undesirable and need to be compensated.
b) Technique of compensation: i.e., how undesirable components should be recognized and compensated.

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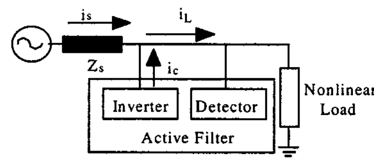


Fig. 1. Block diagram of a parallel active filter.

Obviously, the compensation technique should be developed after clearly defining goals of compensation. Research efforts in the active filtering field have generally focused on compensation techniques and practical considerations [11], [12] with less attention being paid to the aims of compensation. Where the voltages are sinusoidal, cancellation of the current harmonics with reactive power results in unity power factor (UPF) and conversely UPF results in harmonic free currents. So each of the existing compensation strategies is either based on power factor correction such as UPF [4] or on explicit cancellation of harmonics such as p–q theory [3]. Where, both can be used for both harmonic and power factor compensation.

A couple of difficulties arise when the voltages are non-sinusoidal. In this case, the important theoretical key is that regardless of the technique used, perfect compensation of the harmonics and reactive power does not mean UPF is achieved and vice versa. In this case, there are two choices to make:

a) Perfect compensation of the current harmonics, which might not provide unity power factor
b) Unity power factor operation, which does not provide perfect compensation of the current harmonics.

Neither of the above strategies are complete and it is necessary to revise the compensation principle and develop a new strategy with a flexible performance. In this paper, a compromise between harmonics compensation and the power factor correction based on load conditions will be made. Also, it is possible to define the fundamental power factor based on the fundamental currents and voltages. This quantity is independent of voltage and current harmonics and reactive power but does not carry all the power factor concepts.

In this paper, after presenting a short review about the "structure" and "performance" of the existing compensation strategies, a new compensation principle is proposed. Initially, an optimal and flexible control strategy (OFC) for active filtering is proposed. This strategy follows the new compensation philosophy and can optimize the power factor subject to some constraints such as total harmonic distortion (THD) of currents and/or individual harmonics based on IEEE-519 standards. Several simulation results on a realistic system with highly distorted voltages with discussions are presented.

II. P–Q Based and UPF Strategies

A. Classical p–q Compensation Strategy

Evaluating the structure and performance of the existing compensation strategies facilitates developing a new structure for compensation. At present, the classical p–q theory developed by Akagi *et al.* [3] is the state of art and is widely used [11], [12]. Any set of currents i_a, i_b, i_c, and voltages e_a, e_b, e_c in a three-phase four-wire system can be transformed to three-phase orthogonal $(\alpha - \beta - 0)$ coordinates as follows:

$$\begin{pmatrix} f_0 \\ f_\alpha \\ f_\beta \end{pmatrix} = C.\begin{pmatrix} f_a \\ f_b \\ f_c \end{pmatrix}; \quad C = \sqrt{\frac{2}{3}}.\begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{pmatrix} \tag{1}$$

where f can be either voltage, e, or current, i. The instantaneous real power p, the instantaneous imaginary power q, and the instantaneous zero sequence power p_o as defined in [3], are given in the $\alpha - \beta - 0$ frame of reference as

$$\begin{pmatrix} p_0 \\ p \\ q \end{pmatrix} = \begin{pmatrix} e_0 & 0 & 0 \\ 0 & e_\alpha & e_\beta \\ 0 & -e_\beta & e_\alpha \end{pmatrix}\begin{pmatrix} i_0 \\ i_\alpha \\ i_\beta \end{pmatrix} = \begin{pmatrix} p_{0\mathrm{dc}} + p_{0\mathrm{ac}} \\ p_{\mathrm{dc}} + p_{\mathrm{ac}} \\ q_{\mathrm{dc}} + q_{\mathrm{ac}} \end{pmatrix} \tag{2}$$

$p_{\mathrm{ac}}(q_{\mathrm{ac}})$ is that part of $p(q)$ which is produced by the load harmonics. Compensation of the load current is achieved by reducing p_0, p_{ac} and q_{ac} to zero [3], [16]. The compensating currents are obtained as:

$$\begin{pmatrix} i_{0c} \\ i_{\alpha c} \\ i_{\beta c} \end{pmatrix} = \begin{pmatrix} e_0 & 0 & 0 \\ 0 & e_\alpha & e_\beta \\ 0 & -e_\beta & e_\alpha \end{pmatrix}^{-1}\begin{pmatrix} -p_0 \\ -p_{\mathrm{ac}} \\ -q \end{pmatrix}; \qquad e_0 \neq 0. \tag{3}$$

B. UPF Compensation Strategy

In the UPF approach, the three-phase load is compensated in such a way that it behaves like a symmetrical, constant resistive load as follow [4]:

$$[i_\alpha \quad i_\beta \quad i_0] = \psi(t).[e_\alpha \quad e_\beta \quad e_0] \tag{4}$$

where $\psi(t)$ is the conductance of the compensated load which must be a constant for the full compensation , i.e., $\psi(t) = \psi_0$. i_α, i_β, i_0 and e_α, e_β, e_0 are the source currents and the load voltages in the $\alpha - \beta - 0$ frame. The instantaneous power $P(t)$ can be defined as follow:

$$P(t) = \Psi(t).\varepsilon(t); \quad \varepsilon(t) = e_\alpha^2 + e_\beta^2 + e_0^2. \tag{5}$$

The constant ψ_0 is calculated using (6) where P_{dc} and $\varepsilon_{\mathrm{dc}}$ are dc values of $P(t)$ and $\varepsilon(t)$ respectively:

$$\psi_0 = \frac{P_{\mathrm{dc}}}{\varepsilon_{\mathrm{dc}}}. \tag{6}$$

Such a ψ_0 guarantees that the compensated load will be a constant and resistive with UPF.

III. Indirect Compensation Strategies

A. Indirect p–q Compensation Strategy

In the case of sinusoidal voltage condition, the classical p–q method is based on determining the compensating current by calculating the undesirable components of the power quantities $(p,\, q,\, p_0)$. Alternatively, it is possible to determine the desired current of the load by calculating the desired power quantities. For complete compensation, it is necessary to set p equal to a constant and q and p_0 to zero, and then calculate the corresponding desired currents:

$$\begin{pmatrix} i_{0d} \\ i_{\alpha d} \\ i_{\beta d} \end{pmatrix} = \begin{pmatrix} e_0 & 0 & 0 \\ 0 & e_\alpha & e_\beta \\ 0 & -e_\beta & e_\alpha \end{pmatrix}^{-1}\begin{pmatrix} 0 \\ P_{\mathrm{dc}} = p_{\mathrm{dc}} + p_{o\mathrm{dc}} \\ 0 \end{pmatrix} \tag{7}$$

where the subscript "d" means desired components and P_{dc} is the load active power. Equation (7) can be simplified as follow:

$$\begin{pmatrix} i_{0d} \\ i_{\alpha d} \\ i_{\beta d} \end{pmatrix} = \frac{P_{\mathrm{dc}}}{e_\alpha^2 + e_\beta^2}\begin{pmatrix} 0 \\ e_\alpha \\ e_\beta \end{pmatrix}. \tag{8}$$

Next, the compensating currents are calculated by subtracting the desired currents from the original currents of the load as follow:

$$\begin{pmatrix} i_{ad} \\ i_{bd} \\ i_{cd} \end{pmatrix} = C^T.\begin{pmatrix} i_{0d} \\ i_{\alpha d} \\ i_{\beta d} \end{pmatrix}; \quad \begin{pmatrix} i_{ac} \\ i_{bc} \\ i_{cc} \end{pmatrix} = \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} - \begin{pmatrix} i_{ad} \\ i_{bd} \\ i_{cd} \end{pmatrix}. \tag{9}$$

The indirect method has a simpler structure but has no theoretical advantages over the classical one. It can provide a suitable framework which can produce new and more powerful strategies as presented in the next sections. Also, it provides new information about the performance of p–q theory under distorted voltage conditions which will be described later.

B. Perfect Harmonic Compensation (PHC) Strategy

The indirect method is not able to compensate all the current harmonics. But, a simple modification enables it to recognize all the harmonics and sub-harmonics. In the proposed PHC strategy the load active power is calculated as follow:

$$P(t) = i_a e_a + i_b e_b + i_c e_c = P_{\mathrm{dc}} + P_{\mathrm{ac}}. \tag{10}$$

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

$$\begin{pmatrix} i_{0d} \\ i_{\alpha d} \\ i_{\beta d} \end{pmatrix} = \frac{P_{\mathrm{dc}}}{(\overline{e}_\alpha)^2 + (\overline{e}_\beta)^2}\begin{pmatrix} 0 \\ \overline{e}_\alpha \\ \overline{e}_\beta \end{pmatrix} \tag{11}$$

where $\overline{e}_\alpha$ and $\overline{e}_\beta$ are the fundamental components of the load voltages and can be obtained from the original voltages by means of two simple band-pass filters (BPF). Also, P_{dc} is filtered from $P(t)$ using a simple low-pass filter (LPF). Rational term in (11) is a constant and it can be seen that after compensation, the currents will have the same shape of the

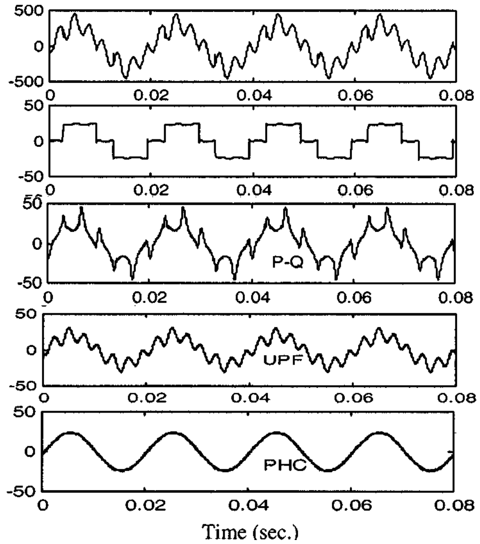


Fig. 2. Top to bottom: Voltage (V), current (A) and calculated results of P–Q, UPF, and PHC currents of phase "a."

fundamental components of voltages in α and β axes. The desired currents calculated using this method are symmetrical and sinusoidal.

IV. Evaluating P–Q, UPF, and PHC Strategies

In this section, using an example the performance of the p–q, UPF, and PHC approaches are evaluated. Shortcoming of p–q has been previously shown in [4]. A three-phase symmetrical and nonsinusoidal voltage set is applied to a three-phase 13.2 kVA 6-pulse thyristor bridge. Using the classical p–q compensation strategy for compensating the $p_{\rm ac}$ and q leads to three-phase compensated currents. Fig. 2 shows one phase voltage and current of the load and the compensated load current resulted from p–q and UPF, and PHC strategies. The currents have been calculated and shown directly from each strategy to avoid any non ideal effect of inverter based compensator. It is seen that the active filter is unable to compensate the current harmonics for p–q and UPF strategies. Moreover, p–q strategy introduces some additional harmonics [4]. Also, it can be seen that the resulting current from PHC strategy is a pure sinusoid.

A. Evaluating P–Q Strategy

Forcing the load instantaneous real power, $p(t)$, to a constant value is not only a suitable approach for compensating the harmonics but also it may cause some additional harmonics in the source currents. Furthermore, some parts of harmonics are active and are embed in the constant term of the real power $p(t)$ as: $p(t) = p_{\rm dc}^f + p_{\rm dc}^h + p_{ac}$ where $p_{\rm dc}^f$ is the active power of the load which is carried by the fundamental component of the current and $p_{\rm dc}^h$ is the active power which is carried by the harmonics. This decomposition indicates that the relation between currents and average power of the harmonics is not a one to one function.

Hence, it is not possible to recognize the harmonics by means of a proper decomposition of real and imaginary powers. Also, (8) shows why the strategy may produce new harmonics. It can be shown that in (8) the rational scalar is a constant at sinusoidal voltage condition but it is time varying under nonsinusoidal voltage condition. This can cause some additional harmonics due to the product of a time varying scalar by the voltage vector.

B. Evaluating UPF Strategy

Based on (4)–(6), the strategy requires currents to have the same shape as voltages. Hence, they will be distorted and unbalanced if voltages are distorted and unbalanced. Also, the UPF strategy is more effective than the PHC in reducing the load voltage harmonics. This is due to the effect of source impedance that can filter out some parts of the source harmonics [4].

V. Optimal and Flexible Control (OFC) Strategy

A. Essential and New Compensation Structure

In order to develop a new compensation structure, the classical p–q, PHC, and UPF strategies can be represented by:

Indirect p–q:

$$\begin{pmatrix} i_{0d} \\ i_{\alpha d} \\ i_{\beta d} \end{pmatrix} = \frac{P_{\rm dc}}{e_\alpha^2 + e_\beta^2} \begin{pmatrix} 0 \\ e_\alpha \\ e_\beta \end{pmatrix} \tag{12}$$

PHC:

$$\begin{pmatrix} i_{0d} \\ i_{\alpha d} \\ i_{\beta d} \end{pmatrix} = \frac{P_{\rm dc}}{(\overline{e}_\alpha)^2 + (\overline{e}_\beta)^2} \begin{pmatrix} 0 \\ \overline{e}_\alpha \\ \overline{e}_\beta \end{pmatrix} \tag{13}$$

UPF:

$$\begin{pmatrix} i_{0d} \\ i_{\alpha d} \\ i_{\beta d} \end{pmatrix} = \frac{P_{\rm dc}}{(e_\alpha^2 + e_\beta^2 + e_0^2)_{\rm dc}} \begin{pmatrix} e_0 \\ e_\alpha \\ e_\beta \end{pmatrix}. \tag{14}$$

Equation (12)–(14) show that the resulting compensated currents from all strategies with very different performances have a similar structure. They can be represented by the product of a scalar, and a vector which is a function of voltages. The above representation facilitates the development of a unified compensation framework that can cover and extend all the above mentioned techniques. The following relation shows the new compensation structure:

$$i^* = \Psi_0^* . e^* \tag{15}$$

ψ_0^* is a constant and $i^* = [i_\alpha^*, i_\beta^*, i_0^*]^T$ is the desired load current vector in the α, β, and 0 coordinates where the superscript "T" means the transpose of the vector. Virtual voltage $e^* = [e_\alpha^*, e_\beta^*, e_0^*]^T$ is generally a filtered version of the load voltage $e = [e_\alpha, e_\beta, e_0]^T$ by the filtering matrix $G(s)$:

$$e^*(s) = G(s).e(s) \tag{16}$$

$e^*(s)$ and $e(s)$ are the Laplace transforms of e^* and e vectors respectively. In this new structure, the desired current vector i^* is considered to have the same shape as the filtered load voltage vector e^* instead of the exact load voltage vector e. $G(s)$ is designed by an optimization algorithm such that the resulting e^*

and i^* provide some desired power quality features like maximizing the power factor or minimizing the total harmonic distortion (THD) of the source currents. These can be taken as objective functions and can be used with an appropriate set of the following constraints.

- Upper bound on THD of the source currents.
- Upper bound on harmonic factors of individual harmonics of the source currents.
- Upper bound on unbalancing factor of the source currents.
- Lower bound on power factor.
- Other conventional power quality considerations such as Telephone Interference Factor (TIF) [17], and practical constraints such as the rating of compensator inverter.

Also, other new power quality indexes which may be introduced in future can be considered. In some cases, rejecting the harmonics because of their impacts on the system may be so important that the power factor can be ignored. In other conditions, a near unity power factor load which has lower line current and provides a better performance in the network [15] may be preferred. Although, the voltage compensation is very important but it should be done using other active filter topologies [7]. Relations (15)–(16) show the following features for the new structure:

- The compensated load will be linear but not necessarily pure resistive and balanced.
- The new structure provides a parameterized harmonic extraction system. It can be programmed based on any desirable current after compensation which may be determined by any of the compensation strategies.
- Only the harmonics which are incorporated in the voltages can be appeared in the currents after compensation.

For example, the following are two suitable compensation strategies based on the above objective functions and constraints. η is the power-factor and H_a^i, H_b^i, H_c^i are the THDs of phase a, b, and c currents respectively. Also, $H_{a,n}^i$, $H_{b,n}^i$, $H_{c,n}^i$ are the harmonic factors of the nth harmonic of the phase a, b, and c currents respectively.

Strategy 1:

Maximize η

Subject to:

$$H_a^i \le \gamma_a, \quad H_b^i \le \gamma_b, \quad H_c^i \le \gamma_c,$$
$$H_{a,n}^i \le \lambda_{a,n}, \quad H_{b,n}^i \le \lambda_{b,n}, \quad H_{c,n}^i \le \lambda_{c,n}$$
$$\frac{i_n^0}{i_1^+} \le u_n^0 \quad \text{and} \quad \frac{i_n^-}{i_1^+} \le u_n^-, \qquad n = 1, 2, \ldots, N$$

where i_n^0, i_n^- and i_n^+ are the source zero, negative and positive sequences for the nth harmonic respectively and can be derived from harmonics in $a-b-c$ phases as follows:

$$\begin{pmatrix} i_n^0 \\ i_n^+ \\ i_n^- \end{pmatrix} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & h_n & h_n^2 \\ 1 & h_n^2 & h_n \end{pmatrix} \begin{pmatrix} i_{a_n}^* \\ i_{b_n}^* \\ i_{c_n}^* \end{pmatrix}; \quad h_n = e^{n(j2.\pi/3)} \tag{17}$$

i_n^0/i_1^+ and i_n^-/i_1^+ are the measures of unbalance for the nth harmonic while u_n^0 and u_n^- are the adjustable bounds on them.

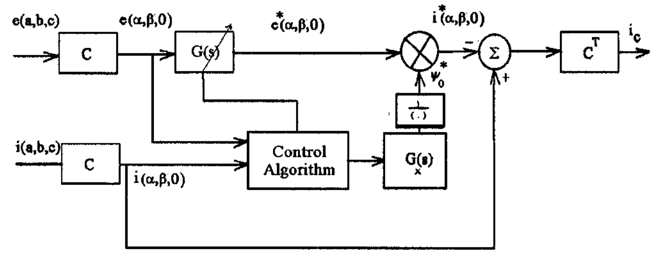


Fig. 3. Block diagram of OFC strategy.

TABLE I
SPECIAL CASES OF OFC WITH DISTORTED VOLTAGES CONDITION

Strategy	G_0	G_α	G_β	G_x	Performance
UPF	1	1	1	LPF	Current harmonics
PHC	0	BPF	BPF	1 or LPF	Lower power factor
p-q	0	1	1	1	Unkown

Constants γ_a, γ_b, γ_c and $\lambda_{a,n}$, $\lambda_{b,n}$, $\lambda_{c,n}$ may be chosen according to the IEC or IEEE standards for harmonics [17]. N is the highest order considered for the voltage harmonics.

Strategy 2:

Minimize $H^i = \omega_1 H_a^i + \omega_2 H_b^i + \omega_3 H_c^i$

Subject to:

$$\eta \ge \eta_0 (\text{lower bound on } \eta)$$
$$H_{a,n}^i \le \lambda_{a,n}, \quad H_{b,n}^i \le \lambda_{b,n}, \quad H_{c,n}^i \le \lambda_{c,n}$$
$$\frac{i_n^0}{i_1^+} \le u_n^0 \quad \text{and} \quad \frac{i_n^-}{i_1^+} \le u_n^-, \qquad n = 1, 2, \ldots, N$$
$$kVA < k$$

where ω_1, ω_2, and ω_3 are adjustable weights and kVA is the active filter rating in kVA and k is its upper limit.

To develop the new strategies 1 and 2, (16) is rewritten as:

$$\begin{aligned} e_\alpha^*(s) &= G_\alpha(s).e_\alpha(s) \\ e_\beta^*(s) &= G_\beta(s).e_\beta(s) \\ e_0^*(s) &= G_0(s).e_0(s) \end{aligned} \tag{18}$$

where $G_\alpha(s)$, $G_\beta(s)$ and $G_0(s)$ are α, β, and 0 coordinates filter banks that process the harmonic components of e_α, e_β and e_0 respectively. Using the above definitions, the average power of the load is derived by (19) where the subscript "dc" means the dc or average value of the quantities:

$$P_{\text{dc}} = (e^T.i^*)_{\text{dc}} = \Psi_0^*(e^T.e^*)_{\text{dc}}. \tag{19}$$

Then, the constant ψ_0^* is calculated in such a way that it does not change the average power of the compensated load.

$$\psi_0^* = \frac{P_{\text{dc}}}{\varepsilon_{\text{dc}}^*}; \quad \varepsilon_{\text{dc}}^* = (e^T.e^*)_{\text{dc}} = (e_\alpha e_\alpha^* + e_\beta e_\beta^* + e_0 e_0^*)_{\text{dc}} \tag{20}$$

Fig. 3 shows the block diagram of the proposed OFC strategy while $G_x(s)$ is a LPF which extracts the dc component of $(e^T.e^*)$ and provides $\varepsilon_{\text{dc}}^* = (e^T.e^*)_{\text{dc}}$. Also, a LPF is used to extract the average power from $P(t)$. Table I shows the conditions on $G_\alpha(s)$, $G_\beta(s)$, $G_0(s)$ that reduce the OFC to the UPF, PHC, and p–q strategies and related performance.

B. Power Factor Study

Generally, the power factor of a three-phase load can be represented as

$$\eta = P_{\rm dc}/E.I^* \tag{21}$$

where E and I^* are the effective values of the voltages and currents of the compensated load. E and I^* are defined as:

$$E = \sqrt{\frac{1}{T}\int_0^T e^T.e.dt} = \sqrt{(e^T.e)_{\rm dc}}$$
$$= \sqrt{(e_\alpha^2 + e_\beta^2 + e_0^2)_{\rm dc}} \tag{22}$$

$$I^* = \sqrt{(i_\alpha^{*2} + i_\beta^{*2} + i_0^{*2})_{\rm dc}}. \tag{23}$$

Using (22) and (23), the power factor of the PHC and OFC can be represented as follows:

$$\eta_{\rm PHC} = \sqrt{\frac{(\overline{e}_\alpha^2 + \overline{e}_\beta^2)_{\rm dc}}{(e_\alpha^2 + e_\beta^2 + e_0^2)_{\rm dc}}} = \sqrt{\frac{(\overline{e}_\alpha^2 + \overline{e}_\beta^2)}{(e_\alpha^2 + e_\beta^2 + e_0^2)_{\rm dc}}} \tag{24}$$

$$\eta_{\rm OFC} = \frac{P_{\rm dc}}{E.I^*} = \frac{P_{\rm dc}}{\psi_0^* E.E^*} = \frac{(e^T e^*)_{\rm dc}}{E.E^*} \tag{25}$$

where E^* is the effective value of the vector e^*. It is easy to show that the power factor η will be equal to one if and only if $e = e^*$ as in the UPF approach. Also, (24) provides the following important result: $\eta_{\rm PHC} \le \eta_{\rm UPF} = 1$.

C. Control Algorithm

Considering the first N terms of the Fourier series for the α-axis load voltage e and e^*, we have

$$e_\alpha = e_{\alpha_0} + \sum_{i=1}^{N} e_{\alpha_i}\cos(i\omega t + \varphi_{\alpha_i}) \tag{26}$$

$$e_{\alpha_i}^* = e_{\alpha_i}.G_\alpha(i), \qquad i = 1, 2, 3, \ldots, N \tag{27}$$

where similar equations can be developed for β, and 0 axes. $G_\alpha(i)$, $G_\beta(i)$, and $G_0(i)$ are the gains of the α, β, 0 coordinate filter banks for the ith harmonic frequency. The phase response of the filters for all harmonic frequencies except for the fundamental component are set to zero as this has no effect on the harmonic cancellation ability of the system and it may decrease the power factor. Neglecting the dc components, E, E^*, and $\varepsilon_{\rm dc}^*$ can be represented by using the Fourier series coefficients of e and filter gains ($G_\alpha(i)$, $G_\beta(i)$, $G_0(i)$) and phase delay of fundamental filters ($\theta_\alpha(1)$, $\theta_\beta(1)$, $\theta_0(1)$) as follows:

$$E^2 = \tfrac{1}{2}\sum_{i=1}^{N}(e_{\alpha_i}^2 + e_{\beta_i}^2 + e_{0_i}^2) \tag{28}$$

$$(E^*)^2 = \tfrac{1}{2}\sum_{i=1}^{N}\left(e_{\alpha_i}^2, G_\alpha^2(i) + e_{\beta_i}(i) + e_{0_i}^2 G_0^2(i)\right) \tag{29}$$

$$\varepsilon_{\rm dc}^* = \tfrac{1}{2}\Bigg\{\sum_{i=2}^{N}\left(e_{\alpha_i}^2 G_\alpha(i) + e_{\beta_i}^2 G_\beta(i) + e_{0_i}^2 G_0(i)\right) + e_{\alpha 1}^2 G_\alpha(1)\mathrm{Cos}\theta_\alpha(1) + e_{\beta_{1i}}^2 G_\beta(1)\mathrm{Cos}\theta_\beta(1) + e_{0_1}^2 G_0(1)\mathrm{Cos}\theta_0(1)\Bigg\}. \tag{30}$$

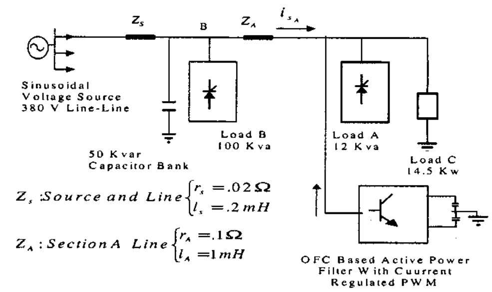


Fig. 4. System under study. Load A to be compensated.

The THD of phase "a" current is given by:

$$H_a^i = \frac{1}{i_{a_1}^*}\sqrt{\sum_{i\neq 1}^{N}(i_{a_i}^*)^2} = \frac{1}{e_{a_1}^*}\sqrt{\sum_{i\neq 1}^{N}(e_{a_i}^*)^2} \tag{31}$$

and

$$\begin{pmatrix} e_{a_i}^* \\ e_{b_i}^* \\ e_{c_i}^* \end{pmatrix} = C^T.\begin{pmatrix} e_{0_i}^* \\ e_{\alpha_i}^* \\ e_{\beta_i}^* \end{pmatrix} = C^T\begin{pmatrix} e_{0_i}.G_0(i) \\ e_{\alpha_i}.G_\alpha(i) \\ e_{\beta_i}.G_\beta(i) \end{pmatrix} \tag{32}$$

while THDs of phases "b" and "c" are similar to (31) and are functions of $G_\alpha(i)$, $G_\beta(i)$, and $G_0(i)$. The desired current of the load i^* is calculated by solving the nonlinear programming problem introduced by strategy 1 or 2 for finding the optimal values of $G_\alpha(i)$, $G_\beta(i)$, $G_0(i)$ and $\theta_\alpha(1)$, $\theta_\beta(1)$, $\theta_0(1)$ where the power factor η is described by (25). Variables E, E^*, and $\varepsilon_{\rm dc}^*$ are calculated using (28)–(30) and the required kVA is calculated by:

$$kVA = E.(i - i^*), \qquad i^* = \psi_0^*.e^*. \tag{33}$$

VI. Case Study and Simulation Results

This section presents the simulation results of the OFC strategy. Although, all different applications and features of OFC due to space limitation are not shown, but they can present some features and flexibility of OFC with new conceptual information.

A. System Under Study

Fig. 4 shows the industrial distribution system under study. Load "B" is a large six-pulse harmonic producing load. It affects the supply voltages of other loads such as load A, which is to be compensated by an active filter. The situation becomes more severe while a capacitor bank is connected for conventional power factor improvement. Under this condition, a resonance near the 7th harmonics will occur between the capacitor and source inductance and provides a highly distorted voltage condition. This situation can better show the flexibility and concept of OFC. Table II shows the parameters of load A and B before and then after installing capacitor. Fig. 5 shows the load A phase "a" current and voltage waveforms and their spectrums using MATLAB/SIMULINK toolbox in details. It is clear that the 7th harmonic has been amplified in the voltage waveform. However, the loads can still work properly.

B. Control Algorithm and Filter Banks

The harmonics of the voltages up to the 11th harmonic ($N = 11$) are considered and each filter bank is constructed by placing

TABLE II
LOAD A AND B PARAMETERS (3 PHASES)

Capacitor :	Without Capacitor		With Capacitor	
Parameters	**Load B**	**Load A**	**Load B**	**Load A**
Current (RMS)	272.69	30.857	278.36	31.508
Current THD (%)	27.66	25.13	30.295	27.09
PhaseVoltage (RMS)	211.7	210.7	232.3	228.9
Voltage THD (%)	12.15	13.44	41.06	40.956
S (kVA)	100	12	106.2	12.492
P (kW)	90	9.8	92.34	10.17
Power Factor	0.900	0.890	0.812	0.814

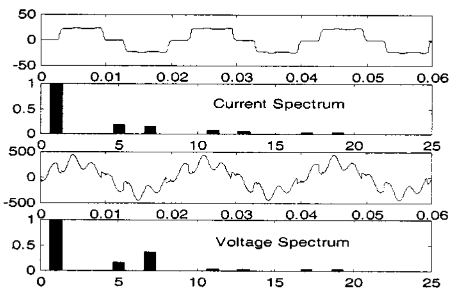
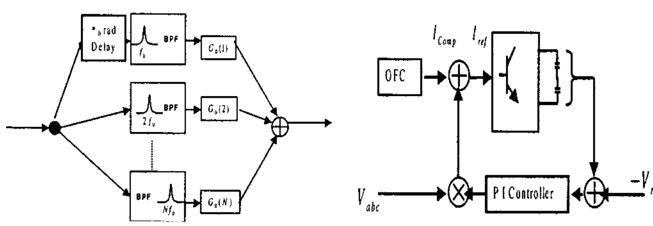


Fig. 5. Waveform and spectrum of phase "a" current and voltage of the nonlinear load A after capacitor connecting at point B. Vertical axis: Amperes or Volts, Horizontal axis: seconds or harmonics order.



(a) (b)

Fig. 6. (a) structure of 0-axis filter bank. (b) DC bus control.

N simple Butterworth band pass filters with center frequencies f_0, $2f_0$, $3f_0$, ..., in parallel, where f_0 is the line frequency (50 Hz) hence higher order harmonics will thoroughly be removed. The bandwidth of each filter is 10 Hz. Fig. 6(a) shows block diagram of a typical filter bank for 0-axis while other axes have similar filter banks.

The control algorithm is simulated using MATLAB® optimization toolbox for compensating two different type of loads, i.e., nonlinear load A and linear load C separately. Optimization is started with all the filter banks gains set to one. That is, initially the algorithm is in UPF mode. Several cases of compensation are considered and the results including the power factor, phase "a" current THD, RMS value of line current (I_d), and required active filter kVA have been shown in Table III.

C. Compensator System

A fast three phase voltage source inverter (VSI) with 3000 μF dc bus capacitors have been used including two proportional–integral controllers in the closed loop. One for dc bus control and another one for good reference signal tracking. Also, current regulated PWM (CRPWM) with double–edged PWM strategy with fixed 20 kHz switching frequency has been used. Value of smoothing inductor in each phase is 4 mH. Fig. 6(b) shows the dc bus control system.

TABLE III
RESULTS OF OFC STRAGETIES 1 AND 2

Harmonics (%) and Filter Constraints					Results				
Case	γ	λ_n	u	kVA Max	PF	Filter kVA	THD (%)	I_d (A)	Comments
1	---	---	--	---	0.9964	7.15	39.7	26.0	Like UPF
2	.1	---	.1	---	0.9273	4.65	0.07	27.9	Like PHC
3	std	std	--	---	0.9434	4.87	5.00	27.4	IEEE-519
4	---	---	--	5	0.9696	5.00	17.6	26.7	kVA Cnst.
5	10	---	--	---	0.9674	4.52	9.65	26.8	***
6	.1	---	--	---	0.9272	4.96	0.07	27.9	Unbalance
7	.1	---	.1	---	0.9265	4.50	0.07	27.9	
10	---	---	--	---	0.95	4.91	17.1	27.2	Strategy 2
11	---	---	--	---	0.9964	1.33	39.7	39.6	Like UPF*
12	.1	---	.1	---	0.9273	6.30	0.07	42.6	Like PHC*
13	std	std	--	---	0.9434	5.49	5	41.9	IEEE-519 *

D. Compensating Non Linear Load A

1) Strategy One—Constraints on THD:

Case 1 (Like UPF): No constraints was placed on the harmonics and so the algorithm presents a behavior like the UPF approach with near one power factor and small deviation from one is due to the fact that the harmonics with higher order than 11 are removed. Fig. 7 shows the phase "a" current of the load for cases 1–4. As seen by this strategy, the compensated current has the same shape as voltage.

Case 2 (Like PHC): The THD upper bounds, γ are chosen so small that the control strategy results like the PHC. But as seen (Table III) the power factor is reduced considerably while the current RMS is increased.

2) Strategy One—IEEE-519 Standard for the Harmonics:

Case 3 (IEEE-519): The THD upper bounds, γ and constraints on individual harmonics are chosen based on IEEE-519 standard [17], while the short circuit ratio at the load "A" point is lower than 20. As seen from Table III and Fig. 7, this situation provides a moderate value for the THD, power factor, and required kVA for the compensator.

3) Strategy One—Constraint on Active Filter kVA:

Case 4: The situation is as in case 1 but active filter rating is limited to 5 kVA. As seen from Fig. 7 this requires the filter do not achieve the UPF since UPF requires higher kVA.

4) Strategy One—Constraints on THD of One Phase:

Case 5: As a case study, one of the load phases has been constrained. The THD constraint is applied only to the current of phase "a" (10%) and so only the current harmonics of phase "a" are reduced. Fig. 8 shows the resulting currents.

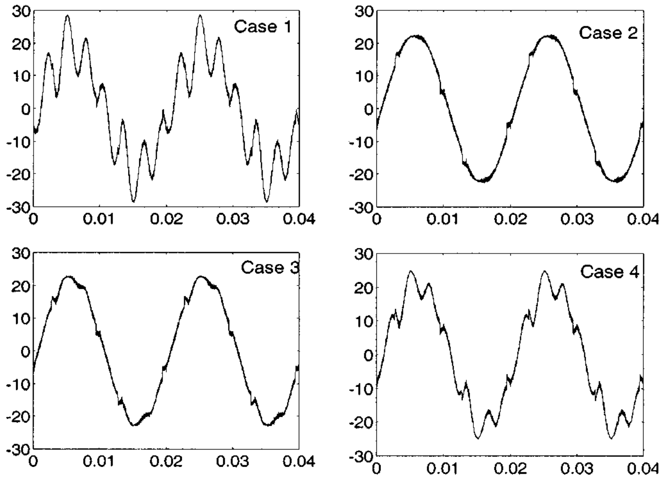


Fig. 7. Resulting currents of OFC strategy for nonlinear load A, Case 1 (like UPF), Case 2 (like PHC), Case 3 (IEEE-519 Standards), Case 4 (UPF with constraints on compensator rating). Vertical axis: Amperes, Horizontal axis: seconds.

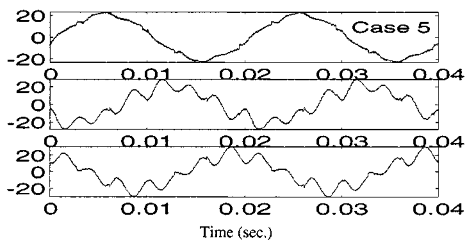


Fig. 8. Resulting currents of Case 5 in amperes.

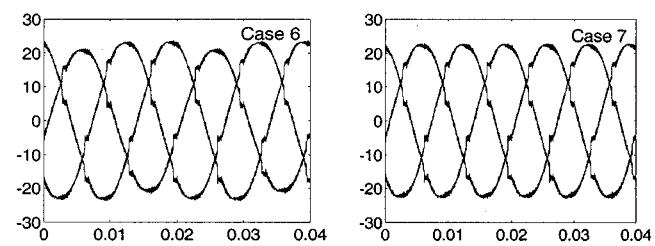


Fig. 9. Resulting currents of Cases 6 and 7. Without (left) and with (right) unbalance constrains. Vertical: Amperes, Horizontal: Seconds.

5) Strategy One—Unbalance Voltages:

Case 6 (Unbalance Voltages): unbalance load voltages may result in unbalance compensated currents regardless of the uncompensated currents be balance or not. In this case, only phase "a" voltage is reduced by 10% and as seen in Fig. 9 the resulting currents are unbalanced.

Case 7 (Unbalance Constraints): the situation is as in case 6 but tight constraints applied to negative and zero sequences and as seen in Fig. 9 (right) the currents are balanced. Table III shows that balancing the currents under unbalanced voltage situation reduces the power factor. However, it might be preferred because of the neutral current impacts caused by unbalanced voltages.

6) Strategy One—Fluctuating Load:

Case 8 (Low Bandwidth LPF): The load A dc current fluctuates by 10 Hz (see Fig. 10). The LPF used for extracting the dc

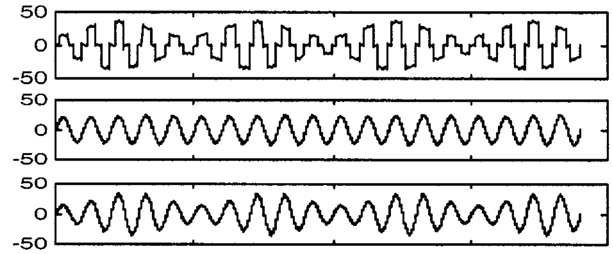


Fig. 10. Top to bottom: Fluctuating load current, Case 8 (with 1 Hz) and Case 9 (with 15 Hz) bandwidth LPF. Vertical: Amperes.

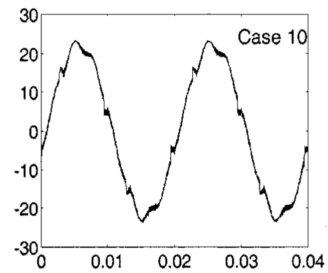


Fig. 11. Result of strategy 2: Case 10 (minimizing THD subject to power factor greater than 0.95). Vertical Axis: Amperes.

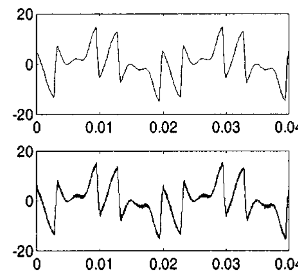


Fig. 12. Case 10 compensating current. Top: reference, Bottom: produced by CRPWM inverter Vertical: Amperes.

power from $P(t)$ and rejecting other components has 1 Hz bandwidth. It provides a current waveform with low fluctuation after compensation. However, this results in a higher dc bus voltage fluctuation ($\pm$10%) like in the conventional methods [3].

Case 9 (High Bandwidth LPF): The situation is as in case 8 but the LPF has 15 Hz bandwidth. So, this provides a fluctuating current waveform after compensation (Fig. 10).

7) Strategy Two—Minimizing THDs:

Case 10: Strategy 2 has been used to reduce the current harmonics while keeping the power factor over 0.95 and weights a, b and c in strategy 2 are chosen to be one. Fig. 11 shows the phase "a" current of the compensated load, while Fig. 12 shows the compensator reference and output currents. If there is no constraint on the power factor, the strategy leads to PHC strategy and results in a lower power factor than 0.95.

E. Compensating the Linear/Resistive Load C

It is important to understand that while the voltages are highly distorted linear loads need to be compensated too. Load C is considered to be compensated (load A: off). Cases 11–13 consider similar load, A, and the numerical results have been shown

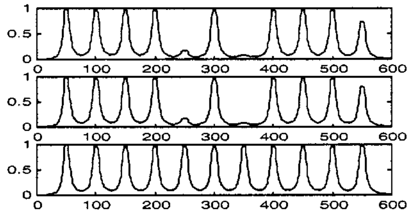
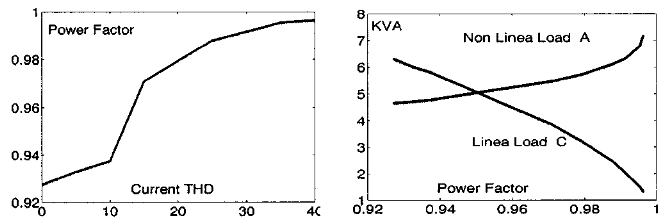


Fig. 13. Resulting filter bank frequency response for Case 3. Top to bottom: a, b, and 0 axis filters. Horizontal Axis: Hertz.



(a) (b)

Fig. 14. (a) Power factor versus current THD after compensation (%). (b) Required filter kVA for loads A and B versus required power factor.

in Table III. Also, as an example, Fig. 13 shows the frequency response of filter banks for case 3.

F. Power Factor/kVA Study and Comparison

Generally, as seen in Table III rejecting the harmonics more than UPF case result in lower power factor. Also, in the unbalance voltage situation, balancing the current provides lower power factor and so higher RMS current after compensation. The kVA rating is not a clear function of the strategy and the constraints used in the study. It also depends on the load characteristics. Generally, higher power factor provides lower rms current for the compensated load but this does not guaranty higher kVA for the active filter. As seen by the results of compensating the nonlinear load A (Table III) UPF requires the highest kVA but PHC requires the least kVA. The situation for linear load C is reverse. UPF requires the least kVA while PHC requires the highest kVA. This is due to the fact that from UPF point of view resistive/balanced load C does not require any compensation. Fig. 14 more clearly states the above concepts. It is shown that increasing the THD increases the power factor but kVA curves have opposite slope due to different characteristics of load A and B.

VII. OFC Implementation Features

Both the current source inverter (CSI) and voltage source inverter (VSI) with reactive dc bus [3], [5] can be used. The dc bus does not require any special control system. Also, fully compensating the time varying loads by OFC, requires a lower bandwidth filter for extraction of $P_{\rm dc}$ from $p(t)$ and this requires a larger compensator as in conventional strategies.

Comparing with PHC, the OFC does not necessarily cancel all the current harmonics and requires a lower expected value for compensator dc bus capacitor, and bandwidth. Comparing to UPF, the OFC strategy like the UPF cancels all the current harmonics, which do not appear in the voltages. Moreover it may further reduce some harmonics to fulfill the harmonic constraints. This occurs at high distortion voltages conditions and at those conditions, the compensator may need larger dc bus capacitor but not wider bandwidth. Also, it is important to notice that OFC is an adaptive control system. It tunes the filter banks based on the load voltage. Once the filter banks parameters updated they do not need to be changed until a change occur on the voltages.

VIII. Conclusion

In this paper, a new concept for load compensation was introduced. It was shown that under distorted voltages conditions an active filter with programmable performance is required. A new optimal and flexible control strategy (OFC) for harmonic compensation in nonsinusoidal voltage conditions is proposed where simultaneous compensation of both power factor and current harmonics is not possible. The control algorithm was formulated using a nonlinear optimization problem. It can be programmed for different types of useful cost functions and desirable constraints, which might be selected based on the power quality and some implementation requirements. OFC is a suitable strategy for achieving the IEEE-519 standards with best power factor with no severe impact on the compensator. It can be adapted for various applications where both the power factor improvement and harmonic cancellation of the load is the goal. Further application of OFC and also realizing it using Neural Networks will be presented in a subsequent paper.

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