IEEE-519-Based Real-Time and Optimal Control of Active Filters Under Nonsinusoidal Line Voltages Using Neural Networks

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***Abstract*—In this paper, a fast and simple neural network (NN)-based control system for shunt active power filters operating under distorted voltage conditions is developed. The proposed system is an enhanced version of the recently developed optimal and flexible control (OFC) strategy with very fast and simple structure. In the proposed system, the time-consuming and complex nonlinear optimization algorithm required by OFC is replaced by a simple 3-layer perceptron NN. The NN is trained off-line using some random data based on the IEEE-519 Standard, while it can be used for a very wide range of new voltage waveforms in practice. The proposed system has been developed after introducing a new version of the OFC strategy in a-b-c frame of reference. This system satisfies both theoretical and practical requirements. Several simulation results using MATLAB toolboxes under highly distorted and unbalanced voltages have been provided to validate the ability of the proposed control system.**

***Index Terms*—Active filters, distorted/unbalanced voltages, IEEE-519 Standards, neural networks (NNs), nonlinear optimization, optimal and flexible control (OFC) strategy.**

I. INTRODUCTION

MODERN active power filters (APFs) were introduced for high-quality compensation of the harmonics of nonlinear loads due to the weaknesses of the conventional passive filters [1]–[4]. Generally speaking, there are two dimensions to the area of active filtering fields: 1) theoretical aspects and 2) practical and economical aspects.

From the theoretical point of view, an active filter should determine and fully compensate all the unwanted harmonics of the load current such as the reactive and unbalanced currents. The important theoretical aspect is the compensation strategy that determines which component of the load current is undesirable and needs to be compensated. It is based on the goal of load compensation. As pointed out in [5], this subject is more important where the voltages are nonsinusoidal. In these conditions, perfect compensation of harmonics with reactive power does not result in unity power factor since some harmonics in the current are useful from power factor point of view and should not be cancelled.

It is very important that an active filter based on the existing and low-cost hardware with low complexity can be developed. Several topologies, such as series and hybrid [6]–[8] and recently, the unified power line conditioner (UPLC) [10] were introduced to improve the performance of APF with attention to reducing the loss and cost of system [9]. One important factor is the required rating of the inverter system and the other one is the cost of signal processing tools for extracting the undesirable currents of the load. The latter is of less importance, but should be considered in a practical design.

Recently, an optimal and flexible control strategy (OFC) for shunt active filters which can compromise between the power factor and current harmonics under distorted voltages conditions via an on-line optimization algorithm has been developed [5]. One drawback is the complexity of the control algorithm, which needs a digital signal processor (DSP) with a complex software program. Another drawback is the time required for the optimization algorithm to provide the optimum filter bank parameters. A fast response is required in the real-time applications such as operation under fluctuating voltage conditions. The major contribution of this paper is to introduce a fast and simple version of OFC system using perceptron neural networks (NNs) with the well-known learning capability [11].

In the proposed NN-based OFC system (NNOFC), the complex and time-consuming optimization algorithm is replaced by a simple perceptron NN. Because of very wide changes in the voltage harmonics, developing such an NN-based system seems to be impossible. However, the system has successfully been developed after introducing a modified version of OFC. In this paper, after a short review of the OFC strategy and its features in Section II, a modified version of OFC, named MOFC, which finds the optimal parameters of filter via a two-part algorithm is introduced in Section III. In Sections IV and V, two NN-based systems with capability of learning based on a compensation strategy with best achievable power factor and satisfying the IEEE-519 Standards [12] for both the balanced and unbalanced voltage conditions are proposed and investigated. The proposed systems are validated using MATLAB-based extensive simulation results which clearly show the implementation features of the proposed system based on the existing DSP processors like the one used in [9]. The results also show a clear and successful application of the NNs in the power quality field.

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II. Optimal and Flexible Control (OFC) Strategy

A. Review of OFC

The OFC structure [5] is as follows:

$$i^* = \Psi_0^* \cdot e^* \quad (1)$$

$$e^*(s) = G(s) \cdot e(s) \quad (2)$$

where 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. Also, $e^*(s)$ and $e(s)$ are the Laplace transforms of e^* and e vectors, respectively. Filter bank set $G(s)$ can be designed based on any defined compensation strategy and by an optimization algorithm.

B. Compensation Strategy

The following is one of the useful load compensation strategies that can be realized by OFC system. This strategy has already been investigated in [5], and will also be considered in this paper.

Strategy 1: $\text{Max}\ \eta(G)$

This is subject to

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

where [5]

η	power-factor;
H_a^i, H_b^i, and H_c^i	total harmonic distortions (THDs) of phase a, b, and c currents, respectively;
$H_{a,n}^i$, $H_{b,n}^i$, and $H_{c,n}^i$	harmonic factors of the nth harmonic of the phase a, b, and c currents, respectively;
i_n^0, i_n^-, and i_n^+	source zero, negative, and positive sequences for the nth harmonic, respectively;
i_n^0/i_1^+ and i_n^-/i_1^+	measure of unbalance for the nth harmonic of the current;
u_n^0 and u_n^-	adjustable bounds on i_n^0/i_1^+ and i_n^-/i_1^+;
N	highest order considered for the voltage harmonics.

The harmonic constraints can be chosen according to the IEEE Standards for harmonics [12].

C. OFC Applications and Features

Results reported in [5] clearly showed the features of the OFC strategy regarding the power factor, harmonics, and filter rating. Generally, the following are the two wide areas of OFC applications:

1) OFC as a compensation tool: the designer chooses a compensation strategy, such as Strategy 1 based on his/her own goal, and then it is realized using the OFC system;
2) OFC as an analysis tool: in this application, one can examine several compensation strategies with different objective functions and constraints and then decide to choose the best strategy. However, this exactly depends on the load characteristics and the desired theoretical and practical parameters.

A highly important feature of OFC is the ability of programming based on any reasonable compensation strategy, such as Strategy 1 or any other unknown strategy. This feature is presented and proved using the following theorem.

D. OFC Theorem

For any desired current vector i_d, after compensation which may be derived based on any compensation strategy, there exists a set of $G_\alpha(i)$, $G_\beta(i)$, $G_0(i)(i = 1, 2, \ldots, N)$, and ψ_0^* which can realize the strategy. $G_\alpha(i)$, $G_\beta(i)$, and $G_0(i)$ are the $\alpha - \beta$ – 0 axis filter bank gains for the ith harmonics. The only constraint on i_d is that it can not contain any harmonic component which does not appear in the voltages. Moreover, the harmonics of the compensated current should be in phase with their corresponding voltages harmonics. This is a very attractive and reasonable constraint since any other harmonics in the current will result in a negative impact on both power factor and THD and should be removed. The proof can be found in Appendix A.

From a practical point of view, OFC has an adaptive structure, which significantly simplifies its implementation. Moreover, it can considerably reduce the required rating of compensator by means of selecting a suitable set of constraints with appropriate limits [5]. In the next section, based on the above compensation strategy a modified version of OFC with a very low optimization time is proposed in the a-b-c frame.

III. Modified OFC (MOFC)

A. Basic Idea

The main idea of this paper is to replace the OFC on-line optimization algorithm by an NN system, which is trained off-line based on some precalculated data. Direct replacement of the optimization process in the OFC by a trained perceptron NN is not possible. Since possibility of large diversity in the voltages does not permit to design a successful NN system with any number of layers and cells. For example, suppose harmonics for each phase of voltage and suppose that different values of each harmonics be quantized into only ten different levels. This shows about 10^{11} different possible waveforms for each phase of voltage. For each voltage waveform, there exists an optimal set of filter banks gains in a simple case where similar waveforms are considered for all phases. This requires the NN to be learned based on a wide range of input data (input voltage harmonics). This diversity in the voltages makes the procedure impossible.

B. MOFC Algorithm

Compensation Strategy 1, which has a cost function with some constraints on individual harmonics and THD, has been decomposed into two subalgorithms. The structure is based on

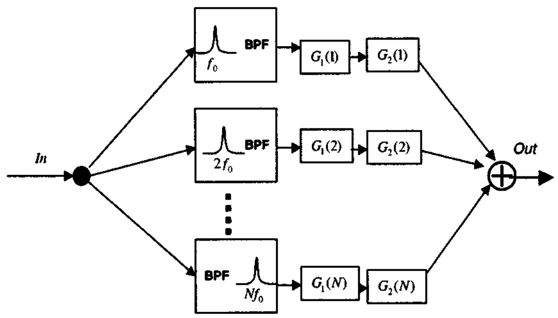

Fig. 1. a-axis filter bank G_a for MOFC.

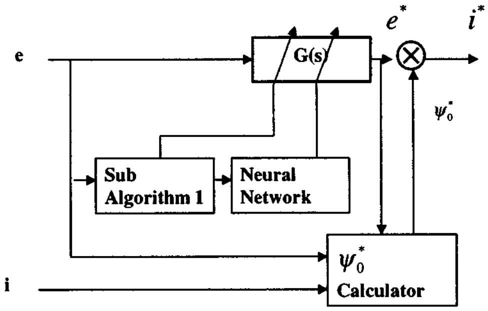

Fig. 2. Block diagram of NNOFC.

(1) and (2), but the quantities are processed in the a-b-c frame of reference and similar waveforms are considered for all phase voltages. $i^* = [i_a^*, i_b^*, i_c^*]^T$ and $e^* = [e_a^*, e_b^*, e_c^*]^T$ are the desired load current and virtual voltage vectors. This similarity enables the strategy to be programmed based on the information of only one phase. Fig. 1 shows the MOFC block diagram of filter bank for phase a where other phases have a similar structure and values. The values of filter banks are calculated in two steps. The final $G(i)$ (filter gain for ith harmonic frequency) is represented by $(i = 1, 2, 3, \ldots, N)$

$$G(i) = G_1(i) \cdot G_2(i). \tag{3}$$

Furthermore, the Fourier series of phase a voltage is as follows:

$$e_a = e_{a_0} + \sum_{i=1}^{N} e_{a_i} \cos(i\omega t + \theta_{a_i}). \tag{4}$$

Applying each $G_1(i)$ and $G_2(i)$ provides new waveforms; therefore, Fourier coefficients for voltages are as follows:

$$e_{a_i}^1 = e_{a_i} \cdot G_1(i) \tag{5}$$
$$e_{a_i}^* = e_{a_i}^1 \cdot G_2(i). \tag{6}$$

A similar representations can be provided for other phases.

1) Subalgorithm A: In this stage, only the constraints on individual harmonics are applied and values of $G_1(i)$s are calculated. Considering the constraints for ith harmonics as $H_{a,n}^i \leq \lambda_{a,n}$, $G_1(i)$ is determined such that related current harmonics are lower than the given constraints as follows:

$$\frac{e_{a_n}^*}{e_{a_1}^*} = \frac{i_{a_n}^*}{i_{a_1}^*} \leq \lambda_{a,n} \Rightarrow e_{a_n}^* \leq e_{a_1}^* \cdot \lambda_{a,n}. \tag{7}$$

Rewriting (7) and using (3), and (5)–(6), we have the following inequality while $e_{a_n}^*$ is the nth coefficient of the virtual voltage of phase a and $n = 1, 2, 3, \ldots, N$:

$$e_{a_n}^* = e_{a_n} \cdot G_1(n) \cdot G_2(n) \leq e_{a_1} \cdot G_1(1) \cdot G_2(1)\lambda_{a,n}. \tag{8}$$

Inequality (8) can be simplified further by

$$G_1(n) \cdot G_2(n) \leq \frac{e_{a_1}}{e_{a_n}} \cdot \lambda_{a,n}. \tag{9}$$

Equation (9) shows the conditions on $G_1(i)$ and $G_2(i)$ that guarantees the fulfillment of the individual harmonics constraints requirement. By taking $G_2(1) = G_1(1) = 1$, and setting $G_2(i)$ to be less than or equal to one, (9) implies the following simple relation for calculating the values of G_1:

$$G_1(n) = \frac{e_{a_1}}{e_{a_n}} \cdot \lambda_{a,n}, \quad n = 1, 2, \ldots, N. \tag{10}$$

2) Subalgorithm B: In this stage, values of G_2 are determined using an optimization algorithm like OFC to optimize the power factor or other objective functions subject to constraints, such as THDs of currents. However, here the input voltages are those which have already been filtered by G_1 and have lower harmonics with respect to the original voltages of load and can significantly reduce the calculation time. Furthermore, as a result of considering the similarity between 3-phase voltages, the cost function and constraints are reduced to the following for finding $G_2(i)$s where E is the effective value of voltages and $G_1(i)$ are known:

$$\text{Max}\, \eta(G_2) = \frac{\frac{1}{2}\sum_{i=1}^{N} 3e_{a_1}^2 G_1(i) \cdot G_2}{E \cdot \sqrt{\frac{1}{2}\sum_{i=1}^{N} 3e_{a_1}^2 G_1^2(i) \cdot G_2^2(i)}}.$$

This is subject to:

$$H_a^i \leq \gamma_a, \quad H_b^i \leq \gamma_b, \quad H_c^i \leq \gamma_c,$$
$$\frac{i_n^0}{i_1^+} \leq u_n^0, \quad \frac{i_n^-}{i_1^+} \leq u_n^-, \quad n = 1, 2, 3, \ldots, N.$$

A similar procedure can be used for the case when voltages are not similar.

IV. Neural Network-Based OFC (NNOFC)

A. Basic Idea

Consider Strategy 1 with IEEE-519 Standards for harmonics [12]. Based on the MOFC procedure, it is possible to use an NN system without an iterative nonlinear optimization algorithm in the second part of MOFC. As mentioned in Section III, a major part of voltage harmonics is significantly reduced by the first part of the MOFC algorithm. Hence, the decision for finding the optimum value of G_2 is based on the voltages with limited values of harmonics that are lower than IEEE-519 Standards. In this situation, it is possible to develop a multilayer NN system. The NN is learned based on a set of pairs of voltages and the corresponding optimum $G_2(i)$, which are obtained by direct optimization. After learning, the NN system will automatically provide the optimum $G_2(i)$ values for any given voltages regarding the second part of the algorithm. Fig. 2 shows the structure of the proposed NNOFC system.

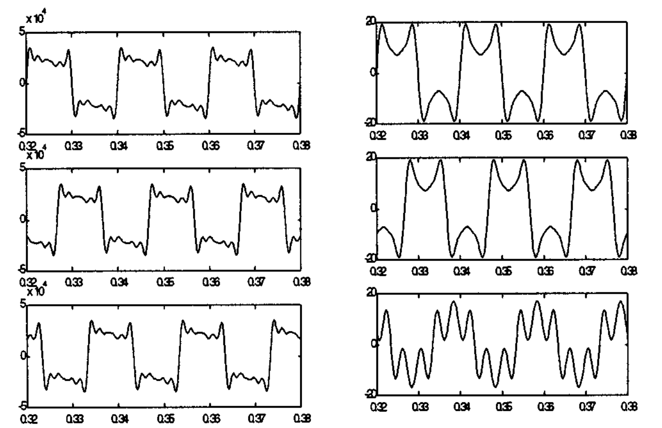

Fig. 3. Load phases a, b, and c waveforms. Left: voltages. Right: currents. Horizontal axis: seconds. Vertical axis: volts/amperes.

B. Decision Based on the Voltage of One Phase

1) System Structure: First, for simplicity, the case in which 3-phase voltages have similar waveforms is considered. A 3-layer perceptron NN system used for NNOFC where $e^1_{a_i}/e^1_{a_1}$ (the normalized values) and $G_2(i)$s are the input and output quantities, respectively. Considering the first N harmonics of voltage since the input vector has been normalized to the amplitude of the first harmonics, the input layer of network needs $N-1$ cells. Also, the output is the set of optimum $G_2(i)$ values which has $N-1$ elements. This is due to the fact that the first harmonics do not need to be controlled. Furthermore, the transfer function f used for each cell is a log-sigmoid function [13].

2) Learning Based on the Back Propagation Algorithm: The voltage set used as learning data has 100 elements and is produced randomly where the harmonic components are limited to the IEEE-519 Standards and the short-circuit ratio is considered to be more than 20 [5], [12]. The Flexibility theorem guarantees the existence of a set of optimal filter bank gains for each random data. The first 11 harmonics of voltage are considered and the NN system has three layers with 10, 24, and 10 cells in Layer 1, Layer 2, and Layer 3, respectively. The back propagation algorithm, the well-known learning algorithm for perceptron networks, has been used while mean square error (mse) has been used as a measure of error [13]. The MATLAB Neural Network Toolbox has been used for designing the NN system and the resulting mse is 1e-5.

3) Simulation Results 1: The most important feature of the network is its ability to provide near optimum response against the new voltages with different harmonics that data used for learning. Several realistic voltage waveforms, such as the system used in [5], are considered and successful response of the proposed NNOFC has been checked. Here, the results of cases with highly distorted voltages, which can better show the performance of NNOFC and MOFC systems, have been presented. The filter banks used in each phase have N filters in parallel with center frequencies $f_0, 2f_0, \ldots, 11f_0$ ($f_0 = 50$ Hz) and with fixed $Q = 10$ ($Q =$ center frequency/bandwidth). For NNOFC, the voltages harmonics have been normalized to the corresponding fundamentals.

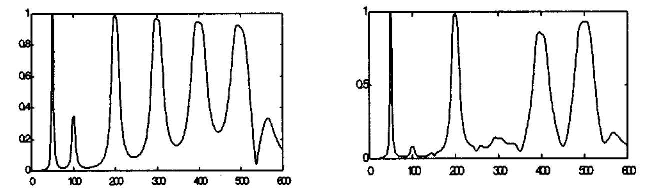

Fig. 4. Filter bank frequency response. Left: MOFC. Right: NNOFC. Horizontal axis: hertz.

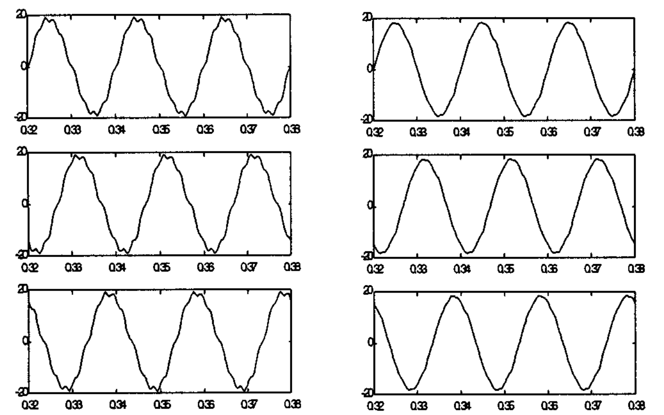

Fig. 5. Resulting compensated currents. Left: MOFC. Right: NNOFC. Horizontal axis: seconds. Vertical axis: amperes.

TABLE I
POWER FACTOR AND THD COMPARISON FOR MOFC AND NNOFC

#	Power Factor			THD(%)		
	without Comp.	MOFC	NNOFC	without Comp.	MOFC	NNOFC
1	0.9263	0.8657	0.8827	59.16	5.00	5.0674
2	0.9528	0.8747	0.8830	57.445	5.00	5.0673

Fig. 3 shows the distorted voltages and currents of a 3-phase load. The resulting filter banks' frequency responses are shown in Fig. 4. Fig. 5 shows the resulting currents after compensation by MOFC and NNOFC systems. Table I shows the power factor and THD of currents before and after compensation for both MOFC and NNOFC systems (#1). The results show the successful behavior of the proposed NNOFC system. The compensated currents in Fig. 5 for MOFC seem very distorted while they have low THDs (about 5%), as shown in Table I. This is due to the existence of the 11th harmonic that has a low effect on THD but provides a visible distortion. This is also an example showing the weakness of the THD factor as a power quality criteria [14]. As seen in Fig. 4, the NNOFC has lower gain than MOFC for the 11th harmonic. Furthermore, it is important to mention that, although some considerable difference between MOFC and NNOFC filter bank frequency responses are visible, there are no considerable voltage harmonics exactly at those frequencies. For these frequencies, the filter bank gains have no effects and the MOFC can be set to have a gain near one without introducing an important effect in the system operation.

4) Simulation Results 2: For further investigating the NNOFC, another set of distorted voltages and currents for the

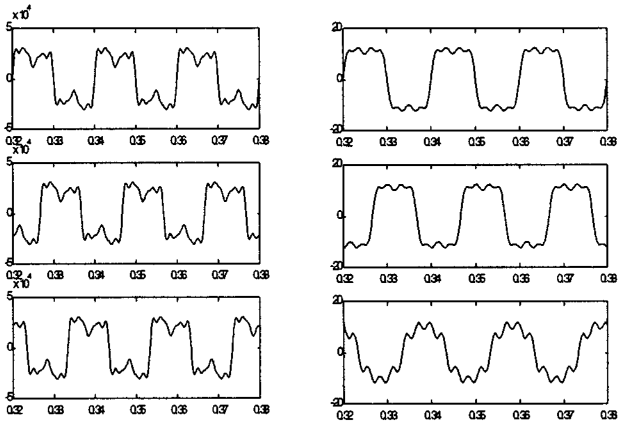

Fig. 6. Load phases a, b, and c waveforms. Left: voltages. Right: currents. Horizontal axis: seconds. Vertical axis: volts/amperes.

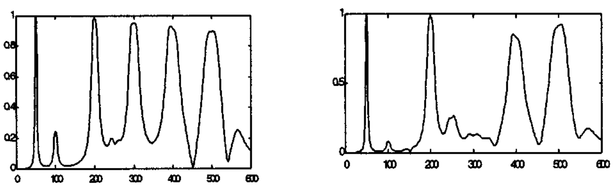

Fig. 7. Filter bank G frequency response. Left: MOFC. Right: NNOFC. Horizontal axis: hertz.

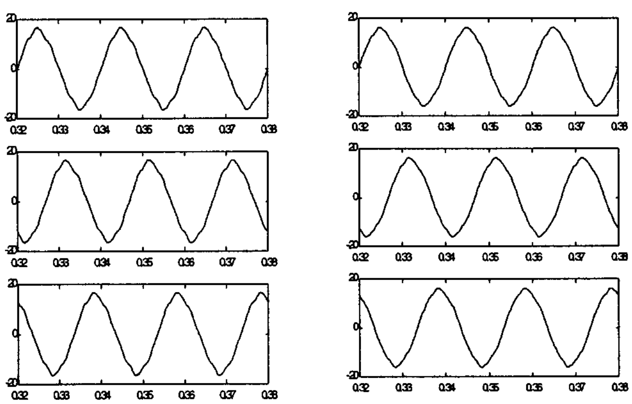

Fig. 8. Resulting compensated currents. Left: MOFC. Right: NNOFC. Horizontal axis: seconds. Vertical axis: amperes.

load have been considered and are shown in Fig. 6. Figs. 7 and 8 show the corresponding filter bank response and currents after compensation for MOFC and NNOFC, which certify the effectiveness of NNOFC system. The power factor and THD of currents before and after compensation are shown in Table I (#2).

C. Decision Based on the Voltages of Three Phases

1) System Structure: In practice, the unbalanced conditions for voltages in the fundamental component and/or harmonics are possible. In this section, the NNOFC system is developed to work under nonsimilar conditions for the three phases of voltages. The same structure as in Section IV-B, with three layers, has been used for NNs. As before, the first 11 terms of voltages harmonics are considered ($N = 11$). However, for this application, it is necessary to consider the N harmonics of each phase. Furthermore, in contrast with the previous method, because of the possibility for unbalanced fundamental voltages, it is necessary to consider the fundamental components as well as the harmonics. This requires considering 311 harmonics components for the voltages; therefore, the related NN system needs 33 cells in both the input and output layers. The developed perceptron-based NN system has 33, 100, and 33 cells in Layer 1, Layer 2, and Layer 3, respectively.

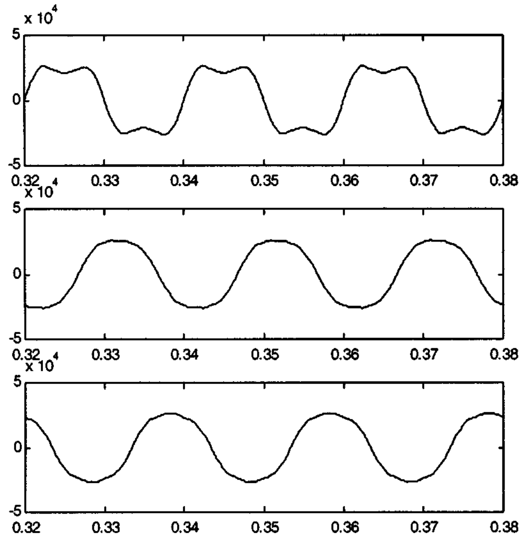

Fig. 9. Unbalanced load voltages of phases a, b, and c. Horizontal axis: seconds. Vertical axis: volts.

2) Learning Based on the Back Propagation Algorithm: The learning data has 100 elements produced randomly based on the IEEE-519 Standards as before, while the constraints u_n^0 and u_n^- are set to be equal to 0.1%. The random generator program has been set to produce voltages data with a maximum of 10% deviation in fundamental voltages, which creates unbalanced conditions for fundamental components of voltages. Furthermore, the input voltages are normalized based on the peak of nominal voltage, i.e., $20\sqrt{2}$ kV, to provide normalized data.

The back propagation algorithm has been used and mse has been used as a measure of error where the resulting mse is about 1e-5. The number of learning data (100) seems to be less, considering the large possible diversity in the voltages harmonics as well as the fact that harmonics of all the voltages should be considered. However, simulation results based on a wide range of new voltages show the successful behavior of the proposed system.

3) Simulation Results 3: In contrast with the original OFC strategy [5], three filter banks have been used for a, b, and c axes, while each filter bank has been constructed by 11 butterworth-tuned filters as before, but with fixed 10-Hz bandwidths. These fixed bandwidths improve the filtering performance of the filter banks, especially for high frequencies. As an example to show the successful performance of the new NNOFC, a new unbalanced 3-phase load voltages waveform has been considered (see Fig. 9) while the currents of the uncompensated load is the same as shown in Fig. 3. Figs. 10 and 11 show the corresponding filter bank G_2 response and currents after compensation for

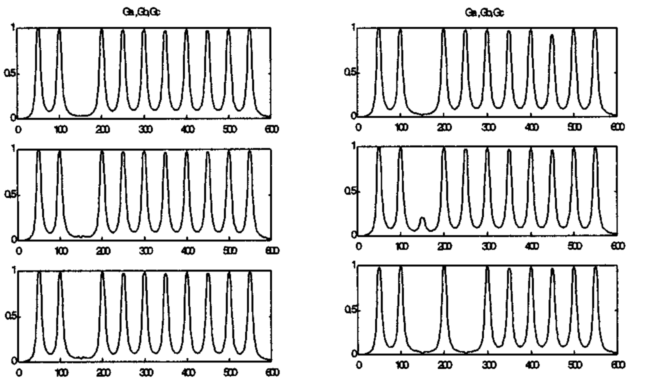

Fig. 10. Top to bottom: filter banks frequency response G_2 for a, b, and c axes. Left: MOFC. Right: NNOFC. Horizontal axis: hertz.

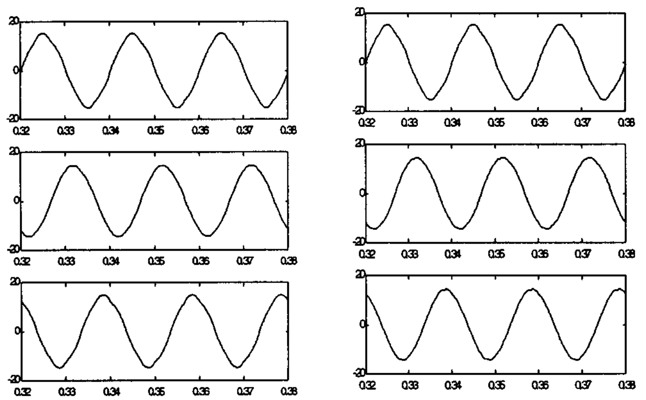

Fig. 11. Resulting three-phase compensated currents. Left: MOFC. Right: NNOFC. Horizontal axis: seconds. Vertical axis: amperes.

MOFC and NNOFC systems. As seen in Fig. 11, it certifies the successful response of the NNOFC system. The response introduced by the NN system is acceptable for applications, especially regarding the unbalanced voltages. However, it should be mentioned that, based on the results of the learning process that showed an mse of approximately 1e-5 for the learning data, the results given in Fig. 10, which seems to have an mse of more than the expected value (i.e., 1e-5), are with relative large errors. In fact, this represents a situation in which the input voltages are sufficiently different from the data used for learning. This shows that under these situations, the system can still provide excellent and applicable results.

V. NNOFC-Based Active Filtering

To better show the practical application of the proposed NNOFC system, the same conditions in [5] for the load voltages and currents have been considered (6-pulse thyristor rectifier). Also, the same trained NNOFC system in the Section IV has been used. The resulting compensated current of phase a is shown in Fig. 12, while a 3-phase current regulated PWM-inverter-based parallel active filter with the same parameters reported in [5] has been used. The resulting power factor is 0.9426 while the corresponding power factor in [5] is 0.9436.

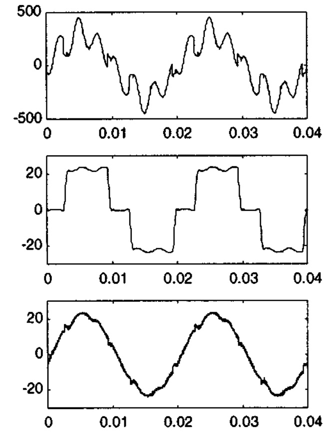

Fig. 12. Top :load phase a voltage. Middle: load phase a current [5]. Bottom: NNOFC-based compensated current of phase a using current regulated PWM inverter [5]. Vertical : volts/amperes. Horizontal axis: seconds.

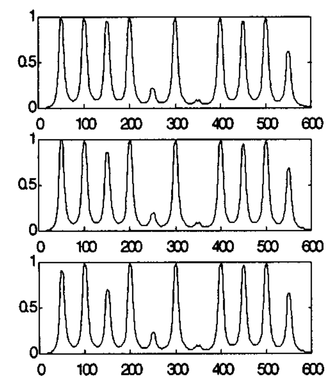

Fig. 13. Top to bottom: NNOFC filter banks frequency response G_2 for a, b, and c axes. Horizontal axis: hertz.

Fig. 13 shows the resulting NNOFC filter banks responses. Comparing the resulting current with the one which appeared in [5] (i.e., the original OFC), clearly shows the successful performance of the proposed NNOFC system.

VI. Conclusions

In this paper, by investigating the recently developed the OFC strategy for active filters under distorted voltages, we have shown that it can be used for implementing any desirable compensation strategy. A modified and fast version of OFC, called MOFC, was developed. MOFC provides the optimum parameters of filter banks via a two-part algorithm, which significantly reduces the required calculation time and hardware. A highly simple, fast, and practical control system using NNs and based on the MOFC concept was developed. The resulting system has exactly both the desired theoretical (good compensation strategy) and practical (simple, fast and cost effective) features. The system can be easily put to the test using existing DSP processors such as Texas Instruments TMS320F24x or Motorola 5680x series. It can also be realized by PC-based hardware with high-level programming.

APPENDIX
PROOF OF OFC THEOREM

Suppose i_d can be any desired current vector after compensation with the above constraints. Based on the Fourier expansion of i_d, the following relations can be derived. $i_{\alpha_{d_i}}$ is the Fourier series coefficient of the ith harmonics in the a-axis component of the i_c where $i = 1, 2, \ldots, N$

$$i_{\alpha_{d_i}} = \psi_0^* \, e_{\alpha_i}^* = \psi_0^* G_\alpha(i) \, e_{\alpha_i} \tag{A.1}$$

$$i_{\beta_{d_i}} = \psi_0^* \, e_{\beta_i}^* = \psi_0^* G_\beta(i) \, e_{\beta_i} \tag{A.2}$$

$$i_{0_{d_i}} = \psi_0^* \, e_{0_i}^* = \psi_0^* G_0(i) \, e_{0_i} \tag{A.3}$$

$$\psi_0^* = \frac{P_{dc}}{\varepsilon_{dc}^*}$$

$$\varepsilon_{dc}^* = (e^T \cdot e^*)_{dc} = (e_\alpha e_\alpha^* + e_\beta e_\beta^* + e_0 e_0^*)_{dc}. \tag{A.4}$$

Equations (A.1)–(A.3) show a set of $3N$ equations with $3N+1$ unknown parameters where $G_\alpha(i)$, $G_\beta(i)$, $G_0(i)$, and ψ^* need to be found. Without loss of generality, suppose $i_{\alpha_{d_1}}$ (and therefore e_{α_1}) is a nonzero component; then both sides of (A.1)–(A.3) can be divided by $i_{\alpha_{d_1}}$. Since $i_{\alpha_{d_i}}$, $i_{\beta_{d_i}}$, $i_{0_{d_i}}$ and e_{α_i}, e_{β_i}, e_{0_i} are the known parameters, hence (A.1)–(A.3) can be reduced to the following: $3N$ linear equations with $3N$ unknown parameters in terms of $G_\alpha(i)/G_\alpha(1)$, $G_\beta(i)/G_\alpha(1)$, and $G_0(i)/G_\alpha(1)$. Hence, there always exists a set of filter banks that can be used for achieving the desired i_d

$$\frac{i_{\alpha_{d_i}}}{i_{\alpha_{d_1}}} = \frac{G_\alpha(i) e_{\alpha_i}}{G_\alpha(1) e_{\alpha_1}}; \frac{i_{\beta_{d_i}}}{i_{\alpha_{d_1}}} = \frac{G_\beta(i) e_{\beta_i}}{G_\alpha(1) e_{\alpha_1}}; \frac{i_{0_{d_i}}}{i_{\alpha_{d_1}}} = \frac{G_0(i) e_{0_i}}{G_\alpha(1) e_{\alpha_1}}. \tag{A.5}$$

Then, ϵ_{dc}^* can be calculated based on the voltages harmonics and filter bank gains using (A.4).

REFERENCES

[1] L. Gyugyi and E. C. Strycula, "Active AC power filters," *Proc. IEEE IAS Conf. Rec.*, 1976.

[2] F. Peng, H. Akagi, and A. Nabae, "A study of active power filters using quad-source PWM converters for harmonic compensation," *IEEE Trans. Power Electron.*, vol. 5, Jan. 1990.

[3] W. M. Grady, M. J. Samotyj, and A. H. Noyola, "Survey of active line conditioner methodologies," *IEEE Trans. Power Delivery*, vol. 5, pp. 1536–1542, 1990.

[4] H. Akagi, "New trends in active filters for line conditioning," *IEEE Trans. Ind. Applicat.*, vol. 32, Nov. 1996.

[5] S. M. R. Rafiei, H. A. Toliyat, and R. Ghazi, "An optimal and flexible control strategy for active filtering and power factor correction under nonsinusoidal line voltages," *IEEE Trans. Power Delivery*, vol. 16, pp. 297–305, Apr. 2001.

[6] M. Aredes and E. H. Watanabe, "New control algorithm for series and shunt three-phase, four-wire active power filters," in *Proc. IEEE Power Eng. Summer Meeting*, 1994.

[7] T. Tanaka and H. Akagi, "A new combined system of active and passive filters to obtain harmonic compensation for large-capacity thyristor converters," *Elec. Eng. Jpn.*, vol. 112, no. 7, 1992.

[8] F. Peng, H. Alagi, and A. Nabae, "Compensation characteristics of the combined system of shunt and series active filters," *IEEE Trans. Ind. Applicat.*, vol. 29, Jan. 1993.

[9] S. D. Round and R. M. Duke, "Real-time optimization of an active filter's performance," *IEEE Trans. Ind. Electron.*, vol. 41, June 1994.

[10] M. Aredes, K. Heumann, and E. H. Watanabae, "An universal active power line conditioner," *IEEE Trans. Power Delivery*, vol. 13, Apr. 1998.

[11] Y.-M. Chen and R. M. O'Connell, "Active power line conditioner with a neural network control," *IEEE Trans. Ind. Applicat.*, vol. 33, July 1997.

[12] *IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems*, IEEE Standard 519-1992, 1993.

[13] *Matlab Neural Networks Tool Box User's Guide*, Mathworks, 1998.

[14] G. T. Heydt and W. T. Jewell, "Pitfalls of electric power quality indexes," *IEEE Trans. Power Delivery*, vol. 13, July 1998.

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