



## Neural-Networks and Synchronous Reference Frame Applied in the Harmonic Compensation with a Three-Phase Parallel Active Power Filter

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**Abstract.** This paper presents an alternative method based on artificial neural network, which is used to obtain the reference currents for harmonic current suppression and reactive power compensation in a shunt active power filter applied to three-phase four-wire system. The neural network consists of a multilayer perceptron, which is trained to estimate the peak amplitude of the load fundamental component currents. The performance of the proposed artificial neural network is evaluated by computer simulation, and it is compared with the method based on synchronous reference frame.

### Key words

Active Power Filter, Artificial Neural Network, Harmonics, Power Quality.

### 1. Introduction

Equipments based on the power electronic connected to the power systems, such as switched power supply, cycloconverters, inverters for driving AC motors, controlled and non-controlled rectifiers for driving DC motors, among others, have been widely used in industrial, commercial and residential applications. However, the currents generated by these nonlinear loads can distort the utility voltages contributing to the degradation of the power quality (PQ) in the electrical power systems. The increasing of non-linear loads makes the use of active power filters an interesting way to eliminate harmonic currents as well as reactive power compensation.

An alternative method to minimize the problems related to the PQ is the use of parallel active power filters (PAPF), which is applied in single-phase systems as well as in three-phase three or four-wire systems [1]-[8]. The PAPF,

based on voltage-source converter, injects compensation currents in order to cancel the harmonic and/or reactive components present in the load current.

Several techniques have been proposed in the literature to produce the compensation reference currents for active power filters.

A method based on the synchronous reference frame (SRF) has been largely used [6], [9]-[11]. Other methods are based on the use of an artificial neural network (ANN) [12]-[15], [18]. Such network can be used in the estimation of the harmonic content in electrical power systems.

This paper proposes an alternative method based on ANN to obtain the compensation reference currents to be used in a PAPF, which is applied to suppress the harmonic currents generated by three single-phase full-wave rectifiers feeding inductive-resistive loads (*RL*), which are connected to a three-phase four-wire system.

The ANN uses the multilayer perceptron architecture in order to estimate the peak amplitude of the load fundamental component currents. Through this peak amplitude and using a synchronous single vector, obtained from a phase-locked loop (PLL) system [16], it is possible to obtain the compensation reference currents to be used by the PAPF.

Simulation results are presented with the purpose of showing the PAPF operation using an ANN for the generation of the compensation reference currents. The proposed method is compared to the SRF method to verify its effectiveness.

The organization of this paper is described as follows: The PAF topology using three full-bridge inverters is presented in Section 2. The SRF method is described in Section 3. The aspects related to the ANN are presented in Section 4. The simulation results of the proposed structure are demonstrated in Section 5. The conclusions of this paper are presented in Section 6.

## 2. Topology of the three-phase PAF

Several topologies of voltage source inverters (VSIs) have been used to implement PAFs, which are applied to three-phase four-wire systems [2]-[8]. In this paper, the PAF structure is performed by means of three full-bridge topology, as shown in Fig. 1 [3], [6].

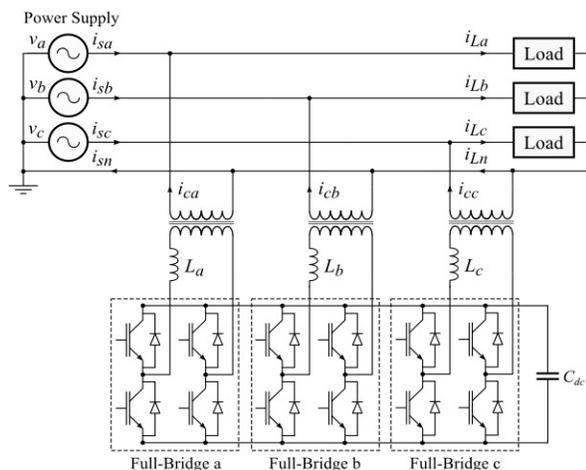


Fig. 1. PAF structure using three full-bridge topologies.

This topology has three full-bridge single-phase inverters connected in each phase of the electrical system allowing independent control of all three phases.

Thus, depending on the compensation strategy chosen, the PAF can perform reactive power compensation and current harmonic suppression. The load unbalance can be taking into account or not. Besides, the three VSI must be connected to the network through isolation transformers because they share the same dc-bus voltage.

## 3. SRF in active power filter applications

Compensators based on the SRF have been used to the harmonic compensation in active power filters, both in three-phase and single-phase systems [6], [9]-[11].

The SRF method proposes the changing of the fundamental terms of voltage and/or current from the *abc*-stationary axes, to continuous quantities in the *dq*-synchronous axes, in which they spin at a synchronous speed in relation to the spatial vectors of voltage and/or current.

The harmonic parcels of voltage or current in the *dq*-axes, which have different frequencies on the synchronous frame, are represented as alternate terms superposed to the

continuous terms. Thus, the fundamental parcels can be extracted by using low-pass filters (LPFs).

A PLL circuit, which is synchronized with the frequency of the electric system, synthesizes the unit vectors  $\sin\theta$  and  $\cos\theta$ , ensuring the necessary orthogonality to the ideal functioning of the system.

### A. SRF applied to single-phase systems

The SRF method will be applied to single-phase systems in order to obtain the compensation reference currents of the PAF.

The compensation strategy will be performed to control each phase independently [3], [6].

This method consists in the individual measurement of the three-phase currents ( $i_{La}$ ,  $i_{Lb}$ ,  $i_{Lc}$ ) and the application of a delay of  $\pi/2$  radians in each of them. The measured load currents are treated as the  $\alpha$ -axis currents of the fictitious two-phase stationary reference frame ( $\alpha\beta$ -axes). Subsequently, the load currents ( $i_{L_{a,b,c}} = i_{\alpha_{a,b,c}}$ ) have a  $\pi/2$  radian phase delay, producing the fictitious quadrature currents in the  $\beta$ -axis ( $i_{\beta_{a,b,c}}$ ).

Therefore, three systems of fictitious two-phase stationary  $\alpha\beta$ -axes can be created as it is seen in (1).

$$\begin{bmatrix} i_{\alpha_{a,b,c}} \\ i_{\beta_{a,b,c}} \end{bmatrix} = \begin{bmatrix} i_{L_{a,b,c}}(\omega t) \\ i_{L_{a,b,c}}(\omega t - \pi/2) \end{bmatrix} \quad (1)$$

For example, the current measured from the phase 'a' ( $i_{La} = i_{\alpha_a}$ ) has a  $\pi/2$  radians phase delay and  $i_{\beta_a}$  is generated, as it can be seen in Fig. 3, where all the phases are considered. Thus, the two-phase fictitious axes are obtained directly from the measured currents, and the transformation from the *abc* stationary three-phase to the  $\alpha\beta$  stationary two-phase system is not necessary.

Thereby, the method only needs of the transformations from the  $\alpha\beta$  stationary two-phase to the *dq* synchronous reference frame, according to the matrix of transformation presented in (2).

$$\begin{bmatrix} id \\ iq \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix} \quad (2)$$

In order to extract the harmonic components of the load currents in the *d*-axis, a high-pass filter (HPF) is used, as implemented according to Fig. 2.

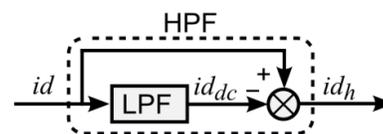


Fig. 2. HPF diagram.

The compensation reference currents of the PAFP ( $i_{ca}^*$ ,  $i_{cb}^*$  and  $i_{cc}^*$ ) are obtained by (3), in which they are obtained directly from the  $dq$  synchronous axes.

$$i_{c_{a,b,c}}^* = \begin{bmatrix} \cos \theta_{a,b,c} & -\sin \theta_{a,b,c} \end{bmatrix} \begin{bmatrix} id_{h_{a,b,c}} \\ iq_{a,b,c} \end{bmatrix} \quad (3)$$

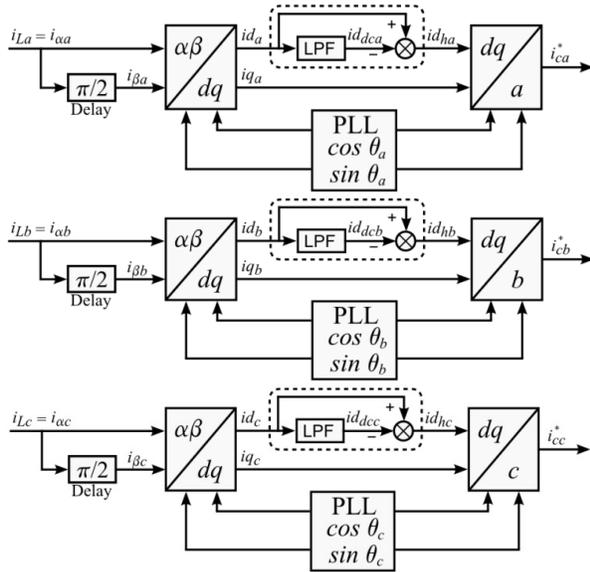


Fig. 3. Block diagrams of the SRF algorithm used individually per phase.

#### 4. Artificial Neural Network

The ANNs represent a technology based on computational technics inspired on the neural biological structure, with the intention of simulating the human brain. These have the capacity of knowledge acquisition and maintenance and can be defined as a set of processing units, characterized by artificial neurons that are interconnected by a great number of interconnections [17]. Fig. 4 shows an artificial neuron diagram.

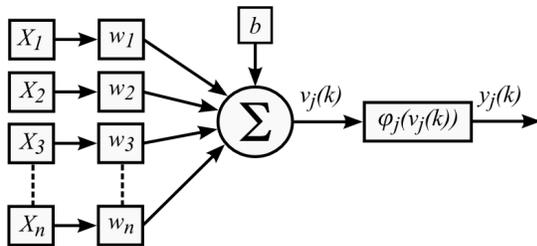


Fig. 4. Artificial neuron representation.

As it was described in [17], the mathematical model that represents the artificial neuron is given by (4) and (5).

$$v_j(k) = \sum_{i=1}^m X_i \cdot w_i + b \quad (4)$$

$$y_j(k) = \varphi_j(v_j(k)) \quad (5)$$

where:

$v_j(k)$  is the answer of the  $j$ -th neuron;

$X_i$  is the  $i$ -th input signal;

$w_i$  is the weight associated to the  $i$ -th input;

$b$  is the threshold of each neuron;

$m$  is the number of neuron input signals;

$y_j(k)$  is the output signal of the  $j$ -th neuron;

$\varphi_j(k)$  is the activation function of the  $j$ -th neuron.

Each artificial neuron calculates its output signal, according to its respective input signal, through the adjustments of the synaptic weights associated to the  $j$ -th output neuron. This adjustment process is done through the calculation of the  $e_j(k)$  error signal in relation to the  $k$ -th iteration of the  $k$ -th input vector, and this is calculated by (6).

$$e_j(k) = d_j(k) - y_j(k) \quad (6)$$

where  $d_j(k)$  is the desired answer of the  $j$ -th output neuron.

Adding all the quadratic errors produced by the exit neurons of the network in relation to the  $k$ -th iteration, it is obtained:

$$E(k) = \frac{1}{2} \sum_{j=1}^p e_j^2(k) \quad (7)$$

where  $p$  is the number of output neurons. In order to obtain a great configuration of weights,  $E(k)$  is minimized through the adjustment of the  $w_{ji}$  synaptic weights. The weights associated to network output layer are recalculated by (8).

$$w_{ji}(k+1) = w_{ji}(k) - \eta \frac{\partial E(k)}{\partial w_{ji}(k)} \quad (8)$$

The  $w_{ji}$  synaptic weight is connected to the  $j$ -th neuron of the layer considered to the  $i$ -th neuron of the previous layer, where  $\eta$  is the constant that determines the learning rate of the retropropagation algorithm. The adjustment of the weights that belong to the hidden layers is done through an analogous way, and it is better described in [17].

##### A. ANN applied in the PAFP

Nowadays, several applications related to the PQ themes using the ANN have been proposed in the literature [12]-[15].

In this paper, a neural network is used in each phase of the PAFP. Each neural network is formed by a multilayer perceptron (MLP), with supervised training. The MLP estimates the peak value of the load fundamental component currents ( $I_{Lpl}$ ), to obtain the compensation reference currents of the proposed PAFP.

Each MLP network is composed by two neural networks, the hidden layer is composed by fifteen neurons and the exit layer is composed by one neuron (Fig. 5). The activation functions used are hyperbolic tangent in the hidden layer and linear in the output layer.

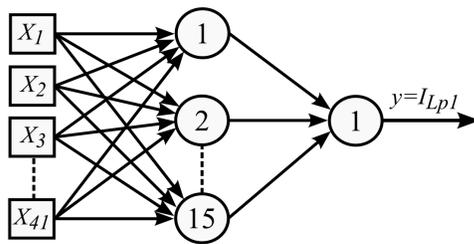


Fig. 5. Structure of the MLP network.

The nonlinear load used to obtain the samples of the MLP network training consists of a single-phase full-wave rectifier with  $RL$  load. Table I shows different power rates of the load.

Table I. Load parameters to ANN training.

Single-phase full-wave rectifier with $RL$ load		
Resistance	Inductance	Power
10 $\Omega$	250 mH	1450 VA
12 $\Omega$	250 mH	1200 VA
14 $\Omega$	250 mH	1050 VA
16 $\Omega$	250 mH	900 VA
18 $\Omega$	250 mH	800 VA
20 $\Omega$	250 mH	720 VA
22 $\Omega$	250 mH	650 VA
24 $\Omega$	250 mH	600 VA
26 $\Omega$	250 mH	550 VA
28 $\Omega$	250 mH	520 VA

For each power level described in Table I, the current signal of the load ( $i_L$ ) was acquired and properly conditioned, to obtain the set of necessary samples to be used in the training process of the MLP network. Fig. 6 shows the block diagram of the process to obtain the samples that were used in the MLP network training.

The desired output of the MLP network is the peak value of the load fundamental component current ( $I_{Lp1}$ ), which is obtained from the LPF output ( $id_{dc}$ ) of the synchronous axis in the SRF method (Fig. 3).

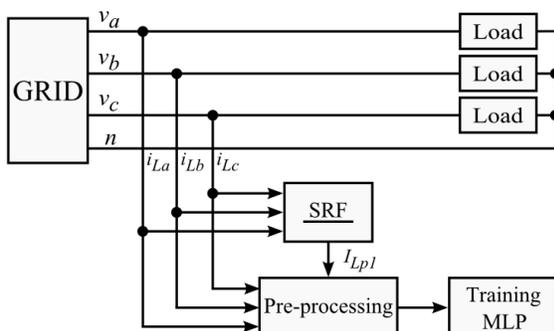


Fig. 6. Diagram of the training process.

## 5. Validation of the MLP network

In order to validate the studies in the MLP network, it was tested in the PAFP through computer simulations. The simulations were carried out considering a three-phase four-wire system, with rms phase voltage of 127 V and a frequency of 60Hz. For the validation, different power rates of the load were used in the training process, according to Table II.

Table II. Load parameters to ANN validation.

Single-phase full-wave rectifier with $RL$ load			
Phase	Resistance	Inductance	Power
A	11.6 $\Omega$	250 mH	1250 VA
B	14.5 $\Omega$	250 mH	1000 VA
C	19.3 $\Omega$	250 mH	750 VA

In the validation process, the MLP network is trained on-line in order to estimate  $I_{Lp1}$ . Using the estimated peak value and the synchronous unit vector ( $\cos\theta$ ), obtained from the PLL system, the fundamental part of the load current ( $i_p$ ) is achieved. Subtracting the quantity  $i_L$  from  $i_p$ , the compensation reference current of the PAFP ( $i_{ca}^*$ ) is obtained.

Fig. 7 shows the block diagram used in the acquiring process of the phase 'a' compensation reference current ( $i_{ca}^*$ ).

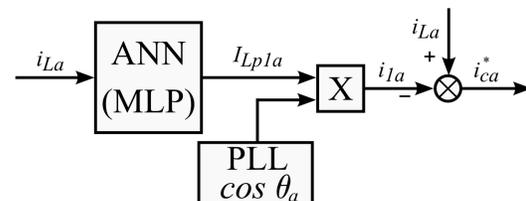


Fig. 7. Block diagram of the compensation reference current ( $i_{ca}^*$ ) acquisition process.

Figures 8 to 11 show the results concerning to the phase 'a'. Fig. 8 shows the comparison between  $I_{Lp1a}$  obtained from both SRF method and MLP network, and the comparison related to the compensation reference currents  $i_{ca}^*$  is shown in Fig. 9.

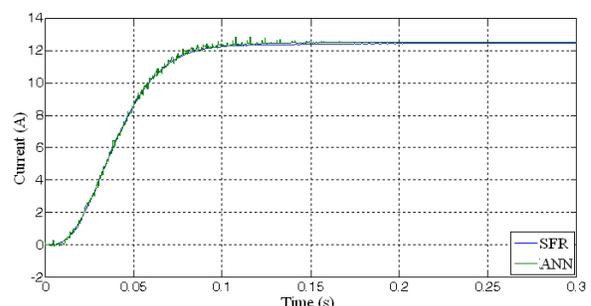


Fig. 8. Peak value of the phase 'a' load fundamental component current ( $I_{Lp1a}$ ).

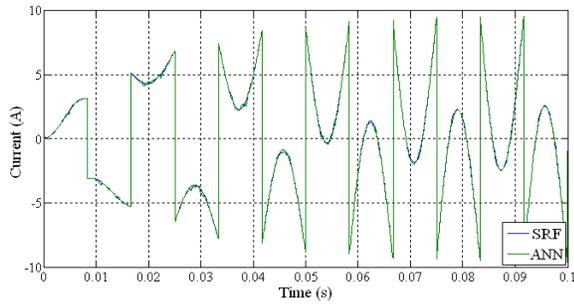


Fig. 9. Phase 'a' compensation reference current ( $i_{ca}^*$ ).

Figure 10 shows the load current ( $i_{La}$ ), source current ( $i_{sa}$ ) and compensation current ( $i_{ca}$ ) synthesized by the PAPPF.

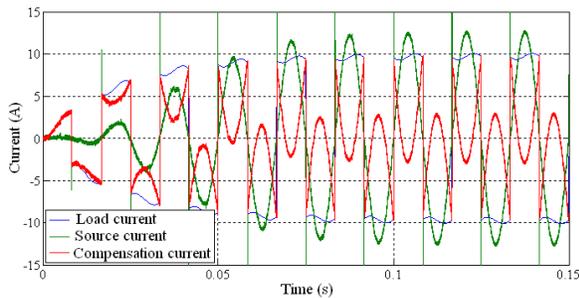


Fig. 10. Phase 'a' currents:  $i_{La}$ ,  $i_{sa}$ , and  $i_{ca}$ .

Figure 11 shows the load current ( $i_{La}$ ) and the source current ( $i_{sa}$ ) when load transient occurs at 0.15s. It is possible to verify the capacity of the MLP operation considering this condition.

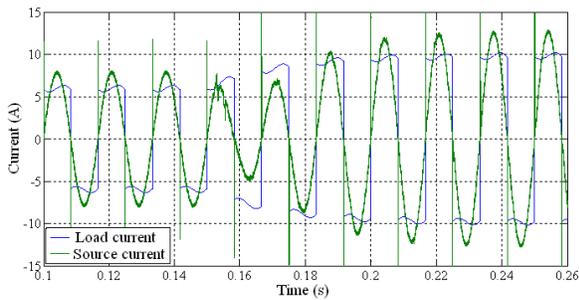


Fig. 11.  $i_{La}$  and  $i_{sa}$  currents for load transient.

Figures 12 and 13 show the load current, source current and the compensation current of the phases 'b' and 'c', respectively.

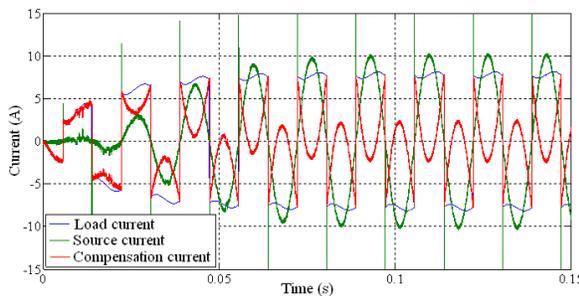


Fig. 12. Phase 'b' currents:  $i_{Lb}$ ,  $i_{sb}$ , and  $i_{cb}$ .

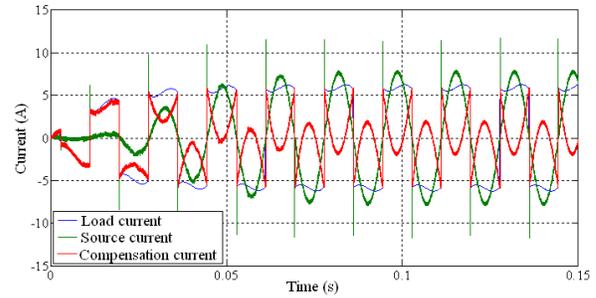


Fig. 13. Phase 'c' currents:  $i_{Lc}$ ,  $i_{sc}$ , and  $i_{cc}$ .

Table III shows the mean relative error (MRE) and the standard deviation (SD), calculated among  $I_{Lpl}$  obtained from the SRF method and the MLP network.

Table III. MRE and SD.

Phases	MRE (%)	SD (%)
A	1.06	1.54
B	1.68	4.85
C	2.26	3.36

Table IV shows the total harmonic distortion (THD) of the three-phase source currents measured after the compensation of the load harmonic currents.

Table IV. Total Harmonic Distortion of the Source Currents (THD%)

Source Currents	$i_{sa}$	$i_{sb}$	$i_{sc}$
Without compensation	47.35	47.31	47.16
SRF method	1.56	1.41	1.55
MLP network	1.59	1.45	1.33

## 6. Conclusion

This paper presented an alternative method, based on neural networks, in order to obtain the compensation reference currents of a three-phase PAPPF used to suppress harmonic currents generated by nonlinear loads.

The MLP network estimated the peak values of the fundamental components of the nonlinear three-phase load currents. Using the fundamental peak values and the synchronous unit vectors obtained from PLL systems, the PAPPF compensation reference currents were obtained.

The validation of the MLP network presented the effectiveness of the proposed ANN in the generation of the reference currents. Besides, the obtained results were very similar to those obtained from the SRF method.

According to the application of the compensation reference currents, it was possible to verify the performance of the PAPPF in suppression of load harmonic currents.

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