A SERIES ACTIVE POWER FILTER WHICH COMPENSATES CURRENT HARMONICS AND VOLTAGE UNBALANCE SIMULTANEOUSLY

Luis Morán*   Pedro Werlinger*   Juan Dixon**   Rogel Wallace*

* Dept. of Electrical Engg.
  Universidad de Concepción
  Casilla 53-C - Concepción - CHILE
  Phone 56-41-234985 ext. 2353
  Fax: 56-41-246999
  Email: l Moran@re noir.die.ud ec.cl

** Dept. of Electrical Engg.
  Universidad Católica de Chile
  Casilla 306-Correo 22 - Santiago
  Phone 56-2-5522375 ext. 4281
  Fax: 56-2-5524054
  Email: jdixon@ing.puc.cl

ABSTRACT

An active power filter connected in series to the power distribution system is presented and analyzed in this paper. The series active power filter is implemented with a PWM voltage-source inverter and operates in conjunction with a resonant LC filter connected in parallel to the power lines and is able to compensate current harmonics and the fundamental negative and zero sequence voltage components generated by nonlinear unbalanced loads. The proposed series active power filter also compensates zero sequence current harmonic components that flow through the neutral conductor.

In particular, the active power filter is discussed in terms of the principles of operations under steady-state and transient operating conditions. The design of the power and control circuits are reported.

I.- INTRODUCTION

Normally, active power filters have been proposed to compensate nonlinear three phase balanced loads [1], [2], [3]. This is a typical situation in industrial power distribution systems where most of the loads are balanced and connected to three wires power systems. However, in urban or rural power distribution systems, most of the loads are single phase connected between phase to neutral, and they generate a large amount of non-characteristics current harmonics [4]. This non-characteristics harmonics return by the neutral conductor overloading power distribution transformers and neutral cables [4].

The topology of the active power filter presented in this paper is shown in Fig. 1. The proposed configuration is based on a three-phase PWM voltage-source inverter connected in series with the power lines through three single phase current transformer. A parallel LC filter must be connected between the nonlinear loads and the current transformers (Fig. 1). Current harmonic and voltage unbalance compensation are achieved by generating the appropriate voltage waveforms with the three-phase PWM voltage-source inverter. Although there are a number of articles which deal with the analysis and design of active power filters connected in series [1] - [3], the three-phase series active power filter presented in this paper differs from previously discussed approaches in the following ways:

a) It is implemented with a three-phase PWM voltage-source inverter.
b) The active power filter is suitable to compensate three-phase systems with three and four wires (three-phases plus the neutral), so that it can compensate current harmonic components generated by three-phase and single phase loads.
c) By compensating the zero sequence harmonics components generated by single-phase loads, the current flowing through the neutral cable is significantly reduced, and the total harmonic distortion of the line currents waveforms are improved.

d) The series active power filter is able to compensate line to line voltage unbalances at the load terminals.

Since the voltage unbalance is caused mainly by fundamental components, with the proposed control scheme, the series active power filter can compensate the negative and zero sequence components of the load voltages and current harmonics simultaneously. Moreover, zero sequence current components flowing through the neutral cable are compensated without sensing the corresponding neutral current thus simplifying the current control scheme.

The treatment presented in this paper includes a comprehensive steady-state and transient analysis of the series active power filter. Also, the design criteria of the power and the control circuit are reported.

Fig. 1. The proposed series active power filter topology.

II.- PRINCIPLES OF OPERATION

It is well known that series active power filters correct current system distortion caused by nonlinear loads by imposing a high impedance path to the current harmonics which forces the high frequency currents to flow through the LC passive filter connected in parallel to the load [1]. The high impedance imposed by the series active power filter is created by generating a voltage of the same frequency that the current harmonic component that needs to be eliminated. Voltage unbalance is corrected by compensating the fundamental frequency negative and zero sequence voltage components present in the system.

2.1.- Control Scheme

The block diagram of the proposed control scheme is shown in Fig. 2. Current and voltage reference waveforms are obtained by using the Park Transformation. Voltage unbalance is compensated by calculating the negative and zero sequence fundamental components of the system voltages. These voltage components are added to the source voltages through the current transformers compensating the voltage unbalance at the load terminals. In order to reduce the amplitude of the current flowing through the neutral conductor, the zero sequence components of the line currents are calculated. In this way, it is not necessary to sense the current flowing through the neutral conductor.

Fig. 2. The block diagram of the proposed series active power filter control scheme.
2.2.- Reference Signals Generator

The compensation characteristics of the series active power filter are defined mainly by the way the reference signals of the control system are obtained. These reference signals must allow current and voltage compensation with minimum time delay. Also it is important that the accuracy of the information contained in the reference signals allow the elimination of the current harmonics and voltage unbalance present in the power system. Since the voltage and current control scheme are independent, the equations used to calculate the voltage reference signals are the following:

\[
\begin{bmatrix}
    v_{a0} \\
v_{a1} \\
v_{a2}
\end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix}
    1 & 1 & 1 \\
    1 & a & a^2 \\
    1 & a^2 & a
\end{bmatrix} \begin{bmatrix}
    v_a \\
v_b \\
v_c
\end{bmatrix}
\] (1)

The voltages \(v_a\), \(v_b\), and \(v_c\) correspond to the phase to neutral voltages before the current transformer (Fig. 1). The reference voltage signals are obtained by making the positive sequence \(v_{a1}\) zero and then applying the inverse of the Fortescue transformation. In this way the series active power filter compensates only voltage unbalance and not voltage regulation. The reference signals for the voltage unbalance control scheme are obtained by applying the following equations:

\[
\begin{bmatrix}
    v_{refa} \\
v_{refb} \\
v_{refc}
\end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix}
    1 & 1 & 1 \\
    1 & a & a^2 \\
    1 & a^2 & a
\end{bmatrix} \begin{bmatrix}
    -v_{ao} \\
    0 \\
    -v_{a2}
\end{bmatrix}
\] (2)

\[
\begin{bmatrix}
i_{aref} \\
i_{bref} \\
i_{cref}
\end{bmatrix} = \begin{bmatrix}
    \frac{2}{\sqrt{3}} & \frac{1}{\sqrt{3}} & 0 \\
    -\frac{1}{\sqrt{3}} & \frac{\sqrt{2}}{\sqrt{3}} & \frac{\sqrt{2}}{\sqrt{3}} \\
    -\frac{1}{\sqrt{3}} & -\frac{\sqrt{2}}{\sqrt{3}} & \frac{\sqrt{2}}{\sqrt{3}}
\end{bmatrix} \begin{bmatrix}
v_\alpha \\
v_\beta \\
v_\alpha
\end{bmatrix} + \begin{bmatrix}
i_0 \\
i_0 \\
i_0
\end{bmatrix}
\]

where \(i_0\) is the fundamental zero sequence component of the line current and is calculated using the Fortescue transformation (4).

\[
i_0 = \frac{1}{\sqrt{3}} (i_a + i_b + i_c)
\] (4)

In (3) \(p_{ref}\), \(q_{ref}\), \(v_\alpha\), and \(v_\beta\) are defined according with the instantaneous reactive power theory [1].

2.3.- Gating Signals Generator

This circuit provides the gating signals of the three-phase PWM voltage-source inverter required to compensate voltage unbalance and current harmonic components. The current and voltage reference signals are added and then the amplitude of the resultant reference waveform is adjusted in order to increase the voltage utilization factor of the PWM inverter for steady state operating conditions. The gating signals of the inverter are generated by comparing the resultant reference signal with a fixed frequency triangular waveform (5 kHz).

The higher voltage utilization of the inverter is obtained if the amplitude of the resultant reference signal is adjusted for the steady state operating condition of the series active power filter. In this case, the reference current and reference voltage waveforms are smaller. If the amplitude is adjusted for transient operating conditions, the required reference signals will have a large value, which will force a higher dc voltage in the inverter thus defining a lower voltage utilization factor for steady state operating conditions.
III.- POWER CIRCUIT DESIGN

The power circuit topology of the series active power filter is composed by the three-phase PWM voltage source inverter, the second order resonant LC filters, the current transformers, and the secondary ripple frequency (Fig. 1). The design of the resonant LC filter is done following the typical design criteria. For this reason it will not be presented in this paper.

The main design characteristics for each of the power components are described below.

3.1.- PWM Voltage-Source Inverter

Since the proposed series active power filter is compensating voltage unbalance and current harmonics simultaneously, the rated power of the PWM voltage-source inverter increases compared with other topologies [1]-[3]. The rated apparent power required by the inverter can be obtain by calculating the apparent power generated in the primary of the current transformer. The voltage reflected across the primary winding of the current transformer is equal to:

\[
V_{\text{series}} = K_1 \left\{ \sum_k I_{sk}^2 \right\}^{1/2} + K_2 \{V_2 + V_0\} \quad (5)
\]

where \(V_{\text{series}}\) is the rms voltage across the primary winding of the current transformer. This voltage is proportional to the rms value of the current harmonic components and to the fundamental negative and zero sequence component of the phase to neutral source voltage. \(K_1\) depends on the LC filter values while \(K_2\) is almost one. The current flowing through the primary winding of the current transformer, due to the harmonic current (eq. 6), can be obtained from the equivalent circuit shown in Fig. 4.

\[
I_{sk} = \frac{V_{\text{series},k} + Z_{fk}I_{Lk}}{Z_{fk} + Z_{sk}} \quad (6)
\]

The dc bus voltage of the inverter depends on the current transformer turn ratio (a), the constant \(K_1\) (eq. 5), and the resultant reference signal voltage.

Fig. 3. The block diagram of the proposed gating signals generator.

Fig. 4. The equivalent circuit of the series active power filter for harmonic components.

3.2.- Current Transformer

The total apparent power required by each current transformer is 1/3 the total apparent power of the inverter. The turn ratio of the current transformer is specified according with the inverter dc bus voltage, \(K_1\) and \(V_{\text{ref}}\). The correct value of the turn ratio “a” must be specified according with the overall series active power filter performance. In general, the turn ratio value of the current transformer must be optimized through the simulation of the overall active power filter, since it depends on the values of different related parameters.

3.3.- Secondary Ripple Filter

The design of the ripple filter connected in parallel to the secondary winding of the current transformer is performed following the method presented in [1]. However, it is important to notice that the design of the secondary ripple filter
depends mainly on the current transformer turn ratio and on the frequency of the triangular waveform used to generate the inverter gating signals. At the carrier frequency of the triangular waveform, the following relation between the ripple filter parameters is satisfied:

\[ X_{\text{ref}} \ll X_{\text{Lrf}} \ll Z_{\text{PWM}} \] (7)

where \( X_{\text{ref}} \) and \( X_{\text{Lrf}} \) are the capacitive and inductive reactance of the ripple filter respectively, and \( Z_{\text{PWM}} \) is the equivalent impedance of the primary circuit at the carrier frequency, reflected to the secondary of the current transformer. The design criteria for \( X_{\text{ref}} \) and \( X_{\text{Lrf}} \) is such that at the ripple frequency the voltage drop in the inductance must be larger than the voltage drop in the capacitor, however for the frequency that needs to be compensated, the voltage drop in the capacitor must be larger than the voltage drop in the inductor.

IV.- CONTROL CIRCUIT DESIGN

Since the control scheme of the series active power filter must translate the current harmonics components that need to be compensate in voltage signals, a proportional controller is used. The use of a PI controller is not recommended since it would modified the reference waveform and generate new current harmonic components. The gain for proportional controller depends on the load characteristics and its value fluctuates between 1 and 2.

Another important element used in the control scheme is the filter that allows to generate \( p_{\text{ref}} \) and \( q_{\text{ref}} \) (Fig. 2). A high-pass first order filter tuned at 15 Hz is used. This corner frequency is required when single non-linear loads are compensated. In this case the dominant current harmonic is the third. The filter implemented is shown in Fig. 5.

V.- SIMULATED RESULTS

The viability of the proposed series active power filter has been verified by simulation using PSpice. Relevant results are shown in Figs. 6, 7, and 8. In particular, Fig. 6 shows the effect of voltage compensation with the current harmonic generator circuit not working, while in Fig. 7, only the current harmonic compensator scheme is operating. In Fig. 8 the series active power filter is compensating voltage unbalances and current harmonic components simultaneously. The simulation circuit is compensating three single phase non controlled rectifiers, each one connected between phase to neutral.

Fig. 6. Simulated waveforms for voltage unbalance compensation. Phase to neutral voltages at the load terminals before and after series compensation. (Current harmonic compensator not operating).
circuits have been presented. Simulated results obtained with Pspice proved the viability of the proposed scheme for transient and steady state operating conditions.

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