POWER QUALITY IMPROVEMENT BY USING ACTIVE POWER FILTERS

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ABSTRACT

This paper describes different power quality problems in distribution systems and their solutions with power electronics based equipment. Shunt, hybrid and series active power filters are described showing their compensation characteristics and principles of operation. Different power circuits topologies and control scheme for each type of active power filter are analyzed. The compensation characteristics of each topology with the respective control scheme are proved by simulation and experimentally.

Index Terms: *Power Quality Improvement, Active Power Filters, Power Electronics, Distribution Systems*

INTRODUCTION

The proliferation of microelectronics processors in a wide range of equipments, from home VCRs and digital clocks to automated industrial assembly lines and hospital diagnostics systems hasincreased the vulnerability of such equipment to power quality problems. These problems include a variety of electrical disturbances, which may originate   in   several ways and have different effects on various kinds of sensitive loads. What were once considered minor variations in power, usuallyunnoticed in the operation of conventional equipment, may now bring whole factories to standstill.As a result of this vulnerability, increasing numbers of industrial and commercial facilities are trying to protect themselves by investing in more sophisticate equipment to improve power quality. Moreover, the proliferation of non-linear loads with large rated power has increased the contamination level in voltages and currents waveforms, forcing to improve the compensation characteristics required to satisfy more stringent harmonics standard. Between the different technical options available to improve power quality, active power filters have proved to be an important alternative to compensate for current and voltage disturbances in power distribution systems. Different active power filters topologies have been presented in the technical literature, and many of them are already available in the market. This paper will focus in the analysis of which to use with their compensation characteristics. Shunt active power filters, series activetopologies,and hybrid schemes will be presented and analyzed. The control scheme characteristics for shunt and

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series schemes will also be discussed. Finally, steady state and transient results for dynamic compensation, obtained from simulated and experimental setup will bepresented.

POWER QUALITY IN DISTRIBUTION SYSTEMS

Most of the more important international standards define power quality as the physical characteristics of the electrical supply provided under normal operating conditions that do not disrupt or disturb the customer's processes. Therefore, a power quality problem exists if any voltage, current or frequency deviation results in a failure or in a bad operation of customer's equipment. However, it is important to notice that the quality of power supply implies basically voltage quality and supply reliability. Voltage quality problems relate to any failure of equipment due to deviations of the line voltage from its nominal characteristics, and the supply reliability is characterizedbyitsadequacyandavailability.

Power quality problems are common in most of commercial, industrial and utility networks.Natural phenomena, such as lightning are the most frequent cause of power quality problems. Switching phenomena resulting in oscillatory transients in the electrical supply, for example whencapacitors are switched, also contribute substantially to power quality disturbances. Also, the connection of high power non- linear loads contributes to the generation of current and voltage harmonic components. Between the different voltage disturbances that can be produced, the most significant and critical power quality problems are voltage sags due to the high economical losses that can be generated. Short-term voltage drops (sags) can trip electrical drivesor more sensitive equipment, leading to costly interruptions ofproduction.

For all these reasons, from the consumer point of view, power quality issues will become an increasingly important factor to consider in order to satisfy good productivity. On the other hand, for the electrical supply industry, the quality of power delivered will be one of the distinguishing factors for ensuring customer loyalty in this very competitive and deregulated market. To address the needs of energy consumers trying to improve productivity through the reduction of power quality related process stoppages and energy suppliers trying to maximize operating profits while keeping customers satisfied with supply quality, innovative technology provides the key to cost-effective power quality enhancements solutions. However, with the various power quality solutions available, the obvious question for a consumer or utility facing a particular power quality problem is which equipment provides the bettersolution.

SOLUTION TO POWER QUALITY PROBLEM

There are two approaches to the mitigation of power quality problems. The first approach is called load conditioning, which ensures that the equipment is less sensitive to power disturbances, allowing the operation even under significant voltage distortion. The other solution is to install line conditioning systems that suppress or counteracts the power systemdisturbances.

A flexible and versatile solution to voltage quality problems is offered by active power filters. Currently they are based on PWM converters and connect to low and medium voltage distribution system in shunt or in series. Series active power filters must operate in conjunction with shuntpassive filters in order to compensate load current harmonics. Shunt active power filters operate as a controllable current source and series active power filters operates as a controllable voltage source. Both schemes are implemented preferable with voltage source PWM inverters, with a dc bus having a reactive element such as a capacitor. Active power filters can perform one or more of the functions required to compensate power systems and improving power quality. As it will be illustrated in this paper, their performance depends on the power rating and the speed of response.Theselection of the type of active power filter to improve power quality depends on the source of the problem as can be seen in Table 1.

Table 1
Active power filters in Power Quality Problem

Active Filter Connection	Load on AC Supply	AC Supply on Load
Shunt	-Current Harmonic Filtering. -Reactive current compensation. -Current unbalance. -Voltage Flicker.	
Series	-Current harmonic filtering. -Reactive current compensation. -Current unbalance. -Voltage Flicker. -Voltage unbalance.	-Voltage sag/swell. -Voltage unbalance. -Voltage distortion. -Voltage interruption. -Voltage flicker. -Voltage notching.

SHUNT ACTIVE POWER FILTERS

Shunt active power filter compensate current harmonics by injecting equal-but-opposite harmonic compensating current. In this case the shunt active power filter operates as a current sourceinjecting the harmonic components generated by the load but phase shifted by 180°. This principle

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is applicable to any type of load considered a harmonic source. Moreover, with an appropriate control scheme, the active power filter can also compensate the load power factor. In this way, the power distribution system sees the non linear load and the active power filter as an ideal resistor. The current compensation characteristic of the shunt active power filter is shown in Fig.1.
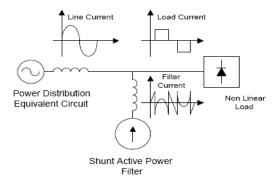

Figure 1: Compensation characteristics of a Shunt active Power filter

Power CircuitTopology

Shunt active power filters are normally implemented with pulse-width modulated voltage source inverters. In thistypeof applications, the PWM-VSI operates as a current controlled voltage source. Traditionally, 2 level PWM-VSI have been used to implement such system. However, in the past years multilevel PWM voltage source inverters have been proposed to develop active power filters for medium voltage applications. Also, active power filters implemented with multiple VSI connected in parallel to a dc bus but in series through a transformer or in cascade has been proposed in the technical literature.
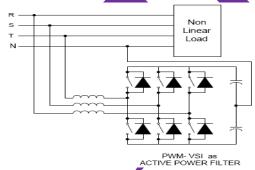

Figure 2: Shunt active power filter topologies implemented with PWM voltage- source inverters.

The use of VSI connected in cascade is an interesting alternative to compensate high power non- linear load. The use of two PWM-VSI of different rated power allows the use of different switching frequencies, reducing switching stresses and commutation losses in the overall compensation system.

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In recent years, there has been an increasing interest in using multilevel inverters for high power energy conversion, especially for drives and reactive power compensation. Multilevel PWM inverters can be connected to high voltage source without a coupling transformer. The use of neutral-point-clamped (NPC) inverters allows equal voltage shearing of the series connected devices in each phase. However, the neutral point potential deviates, resulting in an excess voltage stress to either theupper or lower set of devices.

Basically, multilevel inverters have been developed for applications in high voltage ac motor drives and static var compensation. For these types of applications, the output voltage of the multilevel inverter must be able to generate an almost sinusoidal output current. In order to generate a near sinusoidal output current, the output voltage should not contain low frequency harmoniccomponents.

For active power filter applications the three levels NPC inverter output voltage must be able to generate an output current that follows the respective reference current which contain the harmonic and reactive component required by the load. The power circuit topology of an active power filter implemented with a Neutral-Point- Clamped voltage-sourceinverter is shown in Fig. 3. The three levels NPC voltage- source inverter is connected in parallel through a link reactor to the power distributionsystem.
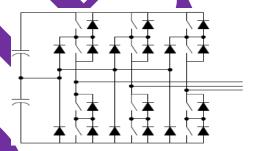

Figure 3: An active powerfilterimplemented   withathree- level NPC voltage-sourceinverter.

ControlScheme

The block diagram of a shunt active power filter control scheme is shown in Fig. 4 and consists of a current reference generator, a dc voltage control and the inverter gating signals generator.

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Figure 4: The block diagram of a shunt active power filter control scheme.

The current reference circuit generates the reference currents required to compensate the load current harmonics and reactive power, and also try to maintain constant the dc voltage across the two electrolytic capacitors. There are many possibilities to develop this type of control [5], [6]. Also, the compensation effectiveness of an active power filter depends on its ability to follow witha minimum error and time delay the reference signal calculated to compensated the distorted load current. Finally, the dc voltage control unit must keep the total dc bus voltage constant and equalsto a given reference value. The dc voltage control is achieved by adjusting the small amount of real power absorbed by the inverter. This small amount of real power is adjusted by changing the amplitude of the fundamental component of the reference current (Figure4).

SERIES ACTIVE POWER FILTERS

It is well known that series active power filters compensate current system distortion caused by non-linear 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 [5]. 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 of thesystem.
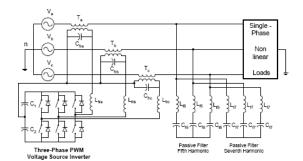
Figure 5: The proposed series active power filter Topology.

ControlScheme

The block diagram of the proposed control scheme is shown in Figure 6. Current and voltage reference waveforms are obtained by using the Instantaneous Reactive Power Theory. Voltageunbalance 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 seriestransformers compensating the voltage unbalance at the load terminals. In order to reduce theamplitude 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 neutralconductor.
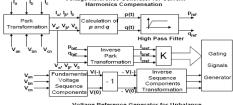

Figure 6: The block diagram of the proposed series

$$i_0 = \frac{1}{\sqrt{3}}\left(i_a + i_b + i_c\right) \qquad (4)$$

Where pref and qref are the instantaneous active and reactivepower associated with harmonics current components.

Reference SignalGenerator

The compensation characteristics of the series active power filter are defined mainly by the algorithm used to generate the reference signals required by the control system. 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 allows the elimination of the current harmonics and voltage unbalance presents in the power system. Since the

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voltage and current control scheme are independent, the equations used to calculate the voltage reference signals are the following:

$$
\begin{pmatrix} v_{a0} \\ v_{a1} \\ v_{a2} \end{pmatrix} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix} \cdot \begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix}
\tag{1}
$$

The voltages **va**, **vb**, and **vc** correspond to the phase to neutral voltages before the series transformer (Fig. 5). The reference voltage signals are obtained by making the positive sequence component, **va1,** 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 followingequations:

$$
\begin{pmatrix} v_{refa} \\ v_{refb} \\ v_{refc} \end{pmatrix} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix} \cdot \begin{pmatrix} -v_{a0} \\ 0 \\ -v_{a2} \end{pmatrix}
\tag{2}
$$

In order to compensate current harmonics generated by the non linear loads, the followingequations are used (Fig.7):

$$
\begin{pmatrix} i_{aref} \\ i_{bref} \\ i_{cref} \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{pmatrix} \begin{pmatrix} v & v \\ -v & v \end{pmatrix}^{-1} \begin{pmatrix} p_{ref} \\ q_{ref} \end{pmatrix} + \frac{1}{\sqrt{3}} \begin{pmatrix} i_0 \\ i_0 \\ i_0 \end{pmatrix}
\tag{3}
$$

Where i0 is the fundamental zero sequence component of the line current and is calculated using the Fortescue transformation (4).

In (3) **pref**, **qref**, **va**, and **vb** are defined according with the instantaneous reactive power theory [5]. The zero sequence fundamental component of the line currents are generated by the source voltage unbalance. Since the system voltage unbalance is eliminated by compensating the negative and zero sequence components present in the source voltage, the magnitude of the fundamental component of the line currents are significantly reduced, and therefore they need not to be compensated by the current control scheme. For this reason, the fundamental component of i0 from equation (3) is

filtered, leaving only the zero sequence harmonic components of i_0 (i_{0ref}), which need to be eliminated from the source line current. Finally, the general equation that defines the references of the PWM voltage-source inverter required to compensate voltage unbalance and current harmonics is the following:

$$
\begin{pmatrix} v_{refa} \\ v_{refb} \\ v_{refc} \end{pmatrix} = K_1 \left[\sqrt{\frac{2}{3}} \cdot \begin{pmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \cdot \begin{pmatrix} v & v \\ -v & v \end{pmatrix}^{-1} \begin{pmatrix} p_{ref} \\ q_{ref} \end{pmatrix} + \frac{1}{\sqrt{3}} \begin{pmatrix} i_{0ref} \\ i_{0ref} \\ i_{0ref} \end{pmatrix} \right] + K_2 \left[\frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix} \begin{pmatrix} -v_{ao} \\ 0 \\ -v_{a2} \end{pmatrix} \right]
$$

$$(5)$$

where K_1 is the gain of the series transformer which defines the magnitude of the impedance for high frequency current components, and K_2 defines the degree of compensation for voltage unbalance, ideally K_2 equals to 1. Also, $i_{0ref} = i_0 - i_{01}$, where i_{01} is the fundamental component of i_0. The block diagram of the control scheme that generates (5) is shown in Figure 7. It is important to note that the references signals calculated with (5) allow the flow of only reactive power between the series active power filter and the compensated power system. In order to compensate voltage regulation, the positive sequence component of the line voltages must be included in (5). The compensation of voltage regulation requires generating active power from the active power filter to the power system. Since there is no active power storage element in this topology, this function cannot be achieved with the proposed scheme.

Gating Signal 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 triangular waveform forces the inverter switching frequency to be constant.
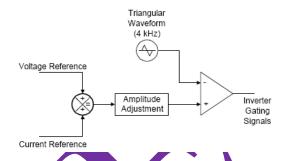

Figure 7: The block diagram of the gating Signal generator

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 isadjusted for transient operating conditions, the required reference signals will have a larger value, which will create a higher dc voltage in the inverter thus defining a lower voltage utilization factor for steady state operatingconditions.

SimulatedResults

The viability of the proposed series active power filter has been verified by simulation using PSpice. Relevant results are shown in Figures 8, 9, and 10. In particular, Figure 8 shows the effect of voltage compensation with the current harmonic generator circuit not working, while in Figure 9, only the current harmonic compensator scheme is operating. In Figure 10 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. The series active power filter starts compensating at 140 ms.
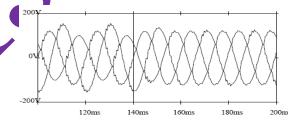

Figure 8: Simulated   waveforms   for   voltage   unbalance compensation.   Phase   to

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neutral   voltages at the load terminals before and after series compensation.   (Current harmonic   compensator notoperating).
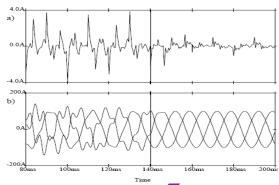

Figure 9: Simulated waveforms for current harmonic compensation. a) Neutral current flowing to the ac mains before and after compensation. b) Line currents flowing to the ac mains before and after compensation. (Voltage unbalance compensator not operating).
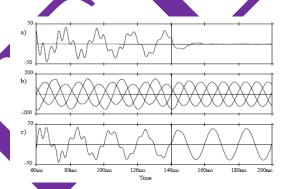

Figure 10: Simulated results for voltage unbalance and current harmonic compensation, before and after compensation. a) Ac mains neutral current. b) Phase to neutral load voltages. c) Ac source line current.

CONCLUSION

In this paper the performance of an active power filter (APF) depends on the inverter characteristics, applied control method, and the accuracy of the reference signal generator. The accuracy of the reference generator is the most critical item in determining the performance of APFs. This paper implemented an efficient reference signal generator composed of an improved adaptive predictive filter. The performance of the implemented reference signal generator was first verified through a simulation withMATLAB

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