AN ACTIVE POWER FILTER IMPLEMENTED WITH PWM VOLTAGE-SOURCE INVERTERS IN CASCADE

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ABSTRACT

A three-phase active power filter implemented with two PWM voltage-source inverters connected in cascade is presented and analyzed in this paper. The active power filter is connected in parallel to the system and can compensate the reactive power and the harmonic current components of high power nonlinear loads. By using two PWM voltage-source inverters in cascade, the compensation characteristics of the active power filter are significantly improved. The voltage-source inverter connected closer to the nonlinear load compensates the reactive power and the low frequency current components required by the nonlinear load, while the second inverter compensates only the high frequency current components. For this reason the first PWM inverter can be implemented with GTO's operating at lower switching frequency while the second inverter can used IGBT's since it has to operate at higher switching frequency. In particular, this paper discusses the proposed scheme in terms of principles of operation, and the analysis under transient and steady state operating conditions. The computer simulation for the proposed active power filter has been done and the results show excellent static and dynamic performances.

I.- INTRODUCTION

With the proliferation of nonlinear loads, including the increasing number of static power converters and electric furnaces, fast acting power filters will have to be considered as an essential component of a power distribution installation. In recent years, active power filters have been researched and developed to suppress harmonics generated by static power converters and large capacity nonlinear power apparatus [1]. Various power circuit configurations have been proposed, and gradually being recognized as a viable solution to the problems created by harmonic components [2].

The topology of the three-phase active power filter presented in this paper is shown in Fig. 1. It can compensate for displacement and distortion power factor. The proposed configuration is based on two three-phase force-commutated pulse-width modulation voltage-source inverters (PWM-VSI) connected in parallel to the nonlinear load. The two inverters are connected in cascade and operate with independent dc voltage and current control schemes. The control system of each PWM-VSI consists of four modules, the current generator circuit, the dc voltage control, the inverter output current control, and the gating signal generator. The current generator circuits uses the concept of Instantaneous Reactive Power [3] to create the required reference signals. The gating signals of each inverter are generated by using a vector control techniques. The proposed vector control technique allows to control the maximum switching frequency of each converter.

Although there are a number of articles which deal with the analysis of active power filters using force-commutated voltage-source inverters connected in parallel [1] - [6], the three-phase active power filter proposed in this paper differs from previously discussed approaches in the following ways:

a) Each PWM voltage-source inverter operates with different switching frequency allowing the generation of specific current harmonic component of the load. In that way, the converter connected closer to the load operates at lower switching frequency (650 Hz) and compensate the reactive power and the low frequency current components required by the load. The second inverter operates at higher switching frequency (2 kHz) and compensates the high frequency current harmonic components that can not be generated by the first converter.
b) Since the converter connected closer to the load will generate a higher rms current and will operate at lower switching frequency, it can be implemented with GTO's or fast thyristors, which can stand highest rms current. The second inverter can be implemented with bipolar transistors or IGBT's since it will operate at higher switching frequency but will generate a lower rms current.
c) Current control in each PWM inverter is achieved with almost constant switching frequency.
d) Current control is done in time domain allowing instantaneous compensation characteristics.
e) By connecting the two inverters in cascade a significant improvement in the active power filter compensation characteristics is achieved since the second inverter will generate all the current harmonic that the first converter is not able to provide.

Moreover, compared with active power filters using quad series PWM inverters [4]-[5], the proposed topology requires less number of converters, a simple and conventional transformer, and a simpler control circuit and compared with active power filters implemented with parallel converters [6], the active power filter proposed in this paper presents a better compensation performance since, by using an independent control scheme, the second converter compensates the current harmonics introduced by the low frequency PWM switching pattern used in the first converter.

The treatment presented in this paper includes a comprehensive steady state and transient analysis of the proposed system. Special emphasis is given to the transient behavior of the active filter while it is compensating a fluctuating nonlinear load. Finally, the validity of the proposed scheme is confirmed by computer simulation.

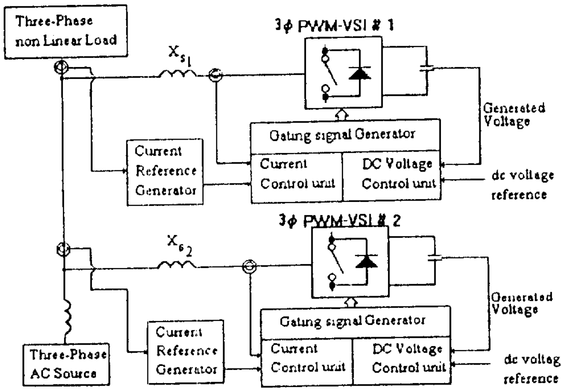


Fig. 1. The proposed active power filter configuration.

II.- PRINCIPLES OF OPERATION

It is well known that active power filters compensate current system distortion caused by nonlinear loads by injecting equal-but-opposite current harmonic components at specific points of a power distribution system [2]. The active power filter compensation characteristics depend mainly on the control strategy. The control system of each PWM inverter has to be able to generate the current reference waveform, maintain the dc voltage constant, and has to generate the inverter gating signals. The principle of operation of the active power filter control system proposed in this paper is presented in the next subsections.

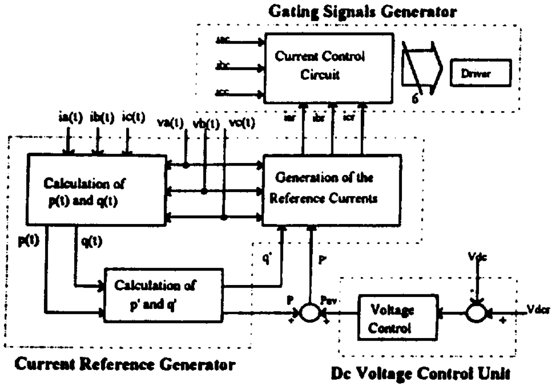


Fig. 2. The block diagram of the active power filter control system.

A) Current Reference Generator

The current reference generator circuit defines the compensation characteristics and accuracy of the active power filter. The reference signals are generated by using the Instantaneous Reactive Power Concept [3] which allows a more flexibility in the active power filter compensation performance. Depending upon the reference signals used the active power filter can compensate only the displacement power factor, only current harmonics or both at the same time. The instantaneous reactive power concept also allows the generation of the reference signals required to control the dc voltage. According with the Instantaneous Reactive Power Theory, the reference currents expressed in α, β reference frame are defined by the following equations [3]:

$$i_{\alpha c} = \frac{-v_\alpha}{v_\alpha^2 + v_\beta^2} p_{ac} + \frac{v_\beta}{v_\alpha^2 + v_\beta^2} q_{dc} + \frac{v_\beta}{v_\alpha^2 + v_\beta^2} q_{ac} \tag{1}$$

$$i_{\beta c} = \frac{v_\beta}{v_\alpha^2 + v_\beta^2} p_{ac} - \frac{v_\alpha}{v_\alpha^2 + v_\beta^2} q_{dc} + \frac{-v_\alpha}{v_\alpha^2 + v_\beta^2} q_{ac} \tag{2}$$

where p_{ac} is the ac component of the active power p(t), q_{dc} and q_{ac} are the dc and the ac components of the reactive power q(t). The dc components are associated with the displacement power factor generated by the fundamental components, while the ac components of p(t) and q(t) are associated with the reactive power generated by harmonics. Since the proposed active power filter will compensate for displacement power factor and harmonic current distortion simultaneously, the current reference waveforms must include the terms multiplied by p_{ac}, q_{ac} and q_{dc}. If

$$p' = -p_{ac} \tag{3}$$

$$q' = -q_{dc} - q_{ac} \tag{4}$$

By replacing (3) and (4) in (1) and (2) and by changing from α, β to *a*, *b*, *c*, reference frame, the active power filter reference currents are defined by:

$$\begin{pmatrix} i_{a\_ref} \\ i_{b\_ref} \\ i_{c\_ref} \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \end{pmatrix} \times \begin{pmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{pmatrix}^{-1} \times \begin{pmatrix} p' \\ q' \end{pmatrix} \tag{5}$$

Equation (5) shows that in order to obtain the reference currents it is necessary to calculate p' and q'. The ac component of the active power, p_{ac}, can be obtained by substracting the dc component, p_{dc}, from the instantaneous active power p(t). This can be easily achieved by using a low pass second order filter. In order to reduce the time response of this filter, normally it is tuned at 150 Hz. However, if low frequency power variations are generated by the nonlinear load, the low pass filter used to generated p' does not allow their compensation, thus the voltage source inverters will experience low frequency dc voltage fluctuation. This problem can be solved by using a low pass filter tuned at a frequency lower than the fundamental (see Fig. 3).

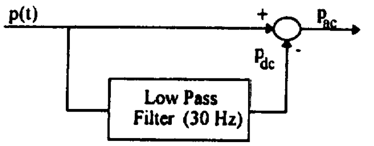


Fig. 3. The block diagram of the power reference generator.

B) Dc Voltage Control Unit

Figure 1 shows that each PWM voltage source inverter is connected to a dc capacitor in the dc bus. Voltage control in the dc bus is performed by adjusting the small amount of real power absorbed by each converter. The real power flowing into each PWM voltage-source inverter depends on the amplitude of the fundamental current component in phase with the respective phase to neutral voltage. From (5) it is found that the reference current of each phase contains a term in phase with the respective phase to neutral voltage, and with an amplitude proportional to P_{ave} which is obtained from the Dc Voltage Control Unit (Fig. 2). By adjusting P_{ave}, each inverter will absorb the real power required to cover the switching losses and to maintain the steady state dc capacitor voltage constant.

C) Gating Signals Generator

The generation of the converter gating signals depends on the current control technique used in the PWM voltage-source inverter. The current control strategy plays an important role in active power filters, since it defines the converter switching frequency, the converter time response, and the accuracy to follow the current references. Also for high power applications it is very important to operate the inverter with a controlled switching frequency, and with a high voltage gain.

In this paper, current control is achieved by using a vector control technique. The current control used in this paper was proposed in [7], and is not a predictive control but a feedback control, which has proved to present a better performance for active power filter applications.

Current Control Technique

Current control is achieved by selecting the inverter output voltage that will minimized the current error signal. This control technique divides the α, β reference frame in six regions (Fig. 4), and then identifies in which region the current error vector, Δi, is located and selects the inverter output voltage that will force the current error to change in an opposite direction, keeping the inverter output current closer to the reference signal. By selecting the inverter output voltage that presents the largest opposite direction component to the current error a faster time response in the current control loop is achieved.

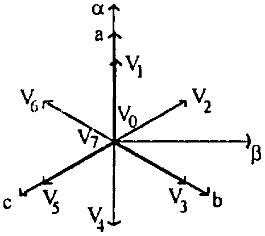


Fig. 4. Hexagon for different region of inverter output voltage.

Figure 5 shows the inverter equivalent circuit connected to load and the power system.

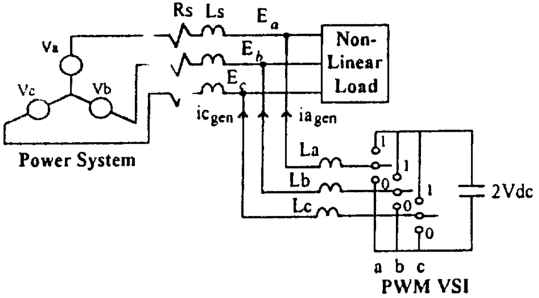


Fig. 5. The PWM voltage-source inverter equivalent circuit.

In Table I, all the possible switching combinations of the inverter are shown. One or zero of the switching functions S_a, S_b, and S_c corresponds to the mode in which the upper side device or the lower side device is on respectively. For each switching combination the inverter output voltage is defined in Table II.

Table I
PWM Voltage-Source Inverter Switching Functions

V(k)	k=0	k=1	k=2	k=3	k=4	k=5	k=6	k=7
(S_a, S_b, S_c)	000	100	110	010	011	001	101	111

Table II
Relationship Between Switching Function and Output Voltage

k	Switch on Phase a	Switch on Phase b	Switch on Phase c	Inverter Output Voltage V(k)
0	4	6	2	0
1	1	6	2	2/3 Vdc
2	1	3	2	2/3Vdc $e^{j\pi/3}$
3	4	3	2	2/3Vdc $e^{j2\pi/3}$
4	4	3	5	2/3Vdc $e^{j\pi}$
5	4	6	5	2/3Vdc $e^{j4\pi/3}$
6	1	6	5	2/3Vdc $e^{j5\pi/3}$
7	1	3	5	0

The equation that relates the active power filter voltages and currents is:

$$V(k) = L\frac{di_{gen}}{dt} + Eo \tag{6}$$

where V(k) is the inverter output voltage, Eo is the phase to neutral source voltage, L is the synchronous inductor, and i_{gen} is the inverter output current. The current error vector, Δi is defined by the expression:

$$\Delta i = i^* - i_{gen} \tag{7}$$

By replacing (7) in (6)

$$L\frac{d\Delta i}{dt} = L\frac{di^*}{dt} + Eo - V(k) \tag{8}$$

If E = Ldi*/dt + Eo then (8) becomes:

$$L\frac{d\Delta i}{dt} = E - V(k) \tag{9}$$

Equation (9) represents the active power filter state equation and shows that the error current vector variations, $d\Delta i/dt$, can be controlled by selecting the appropiate inverter output voltage vector V(k).

Selection of the Switching Mode

The selection of the switching mode is defined by the region in which the current error vector is located. Figure 6 shows the six regions defined by the inverter output voltage vector, while Fig. 7 illustrates the six regions defined by the inverter output current vector. The two hexagones are phase-shifted by 30 degrees.

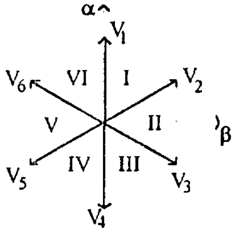


Fig.6. The hexagone defined by the inverter output voltage vector.

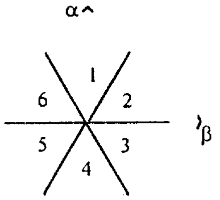


Fig.7. The hexagone defined by the inverter output current vector.

The selection of the inverters switching mode can be explained assuming that E is located in Region I (Fig. 6) and Δi in Region 6 (Fig. 7). The voltage vectors located closer to E are V_1 and V_2. The vectors $E-V_2$ and $E-V_1$ define two vectors $Ld\Delta i/dt$, located in regions III and IV respectively. In order to reduce the error current vector Δi, $Ld\Delta i/dt$ must be located in region III thus V(k) has to be equal to V_1. If the same analysis is done for all the possible combinations, the inverter switching modes for each location of Δi and E can be defined (Table III).

Table III
Inverter Switching Mode

E Region	Δi Region					
	1	2	3	4	5	6
I	V_1	V_2	V_2	$V_0 - V_7$	$V_0 - V_7$	V_1
II	V_2	V_2	V_3	V_3	$V_0 - V_7$	$V_0 - V_7$
III	$V_0 - V_7$	V_3	V_3	V_4	V_4	$V_0 - V_7$
IV	$V_0 - V_7$	$V_0 - V_7$	V_4	V_4	V_5	V_5
V	V_6	$V_0 - V_7$	$V_0 - V_7$	V_5	V_5	V_6
VI	V_1	V_1	$V_0 - V_7$	$V_0 - V_7$	V_6	V_6

Table III shows that the switching function is determined by the region in which Δi and E are located. It is important to note that it is not necessary to know the magnitude of the error current vector, thus simplifying the current control circuit implementation. In case Δi needs to be changed faster it is necessary to determine which vector E-V(k) presents the higher component in the oppositve direction to Δi. For the example shown previously, E-V_6 represents the best solution (Fig. 8).

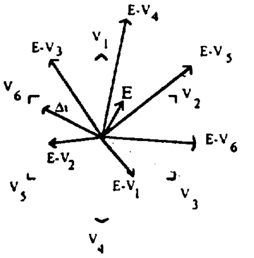


Fig. 8. Representation of all possible E-V(k) vectors.

Table IV shows the switching mode in case Δi becomes large in transient state and needs to be changed faster.

Table IV
Switch Mode Combination for Larger Changes en Δi

Δi Region	V(k)
1	V(1)
2	V(2)
3	V(3)
4	V(4)
5	V(5)
6	V(6)

Table III shows the inverter switching modes when Δi experiments small changes and in Table IV the switching modes required when Δi becomes large in transient state are defined. The control circuit must be able to identify the switching modes that will apply. For that a relationship is defined between the two references; that is $h = \alpha + \delta$, where α is some margin.

Switching Frequency Control

The two hexagon that defines the switching modes characteristics are shown in Fig. 9.

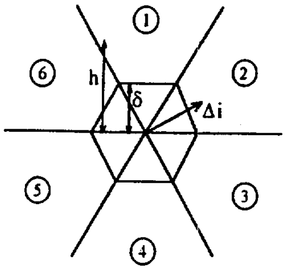


Fig. 9. Hexagons that defines the switching criteria.

If Δi is located below the δ region no commutation is applied to the inverter. If Δi is located between δ and *h*, the switching modes shown in Table III must be applied, and if Δi passes through the *h* hexagon, then the control system is switched over to the faster loop and applies the switching modes defined in Table IV. Once the current control circuit has selected the region where V(k) must commutated, it verifies the time that has passed since the last commutation, and then it compares with the switching frequency selected for the inverter. If the time is higher or equal to $1/2f_c$ a new switching function is applied to the inverter semiconductors. Figure 10 shows the block diagram of the inverter current control scheme.

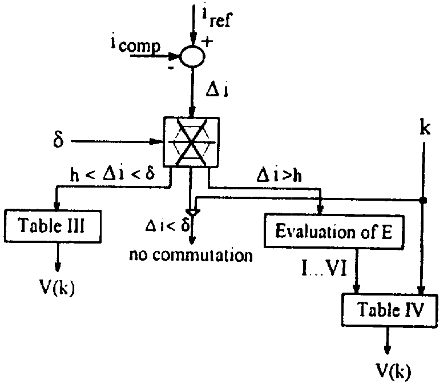
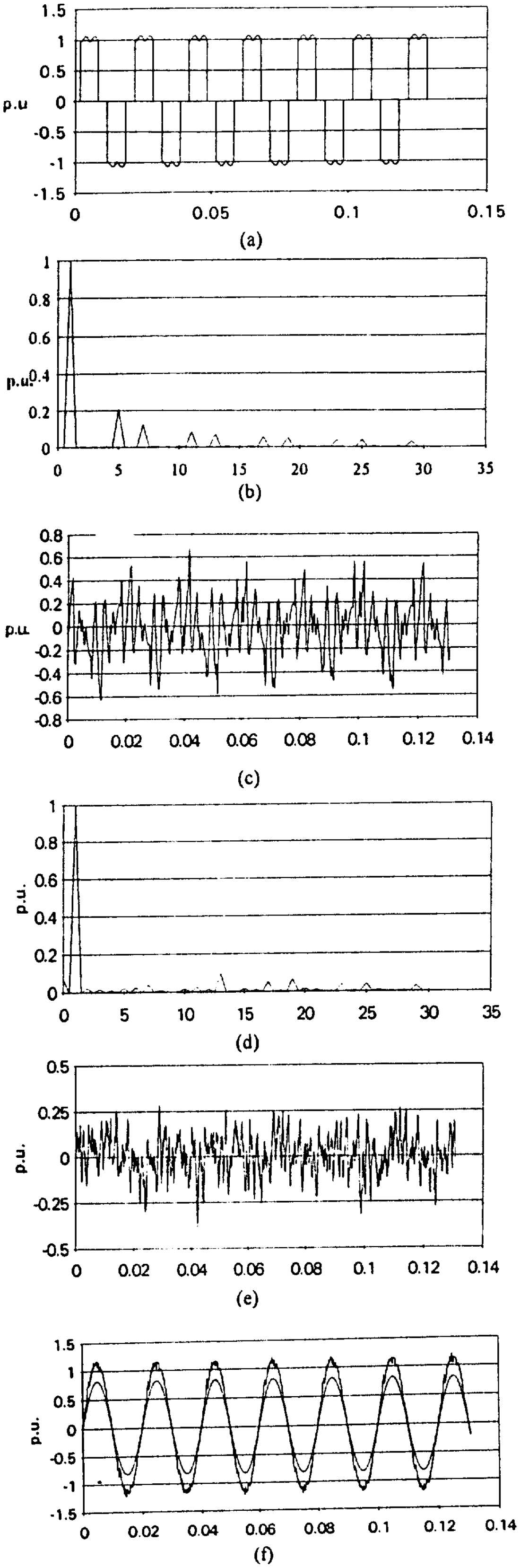


Fig. 11. The block diagram of the current control scheme.

III.- SIMULATED RESULTS

The steady state and transient performance of the active power filter presented in this paper is proved by computer simulation. The steady state compensation characteristics of the active power filter while compensates a six step controlled rectifier are shown in Fig. 12. Specifically, Fig. 12-(f) and 12-(g) show the line current and its frequency spectrum. The frequency spectrum is low and the line current is in phase with the respective phase-to-neutral voltage. This proves the effectiveness for steady state compensation. Transient behavior of the active power filter is proved for the compensation of a step change in the gating signals of the controlled rectifier. Simulated waveforms are illustrated in Fig. 13. Figure 13-(c) shows that the line current is almost sinusoidal and remains in phase with the respective phase to neutral voltage. Finally, in Fig. 14 the good compensation performance of the active power filter while compensating a low frequency power load fluctuation is demonstrated. This figures show the influence of the low pass filter implemented to obtain the reference signals. Figures 14-(b) show that if the second order low pass filter is tuned at 150 Hz the active power filter is not,able to compensate this power fluctuation. This problem is solved by decreasing the resonant frequency of the filter as shown in Fig. 14-(d).



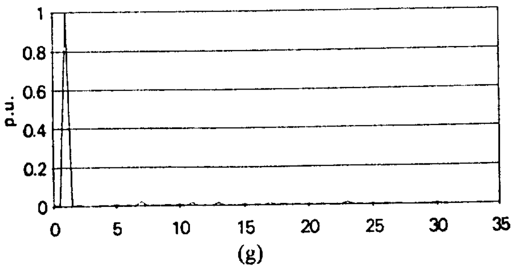


Fig. 12. Simulated steady state results for nonlinear load compensation. (a) The load current. (b) The load current frequency spectrum. (c) The line current generated by the inverter operating at low switching frequency. (d) The inverter line current frequency spectrum. (e) The line current generated by the inverter operating at higher switching frequency. (f) The power system line current and the respective phase to neutral voltage. (g) The power system line current frequency spectrum.

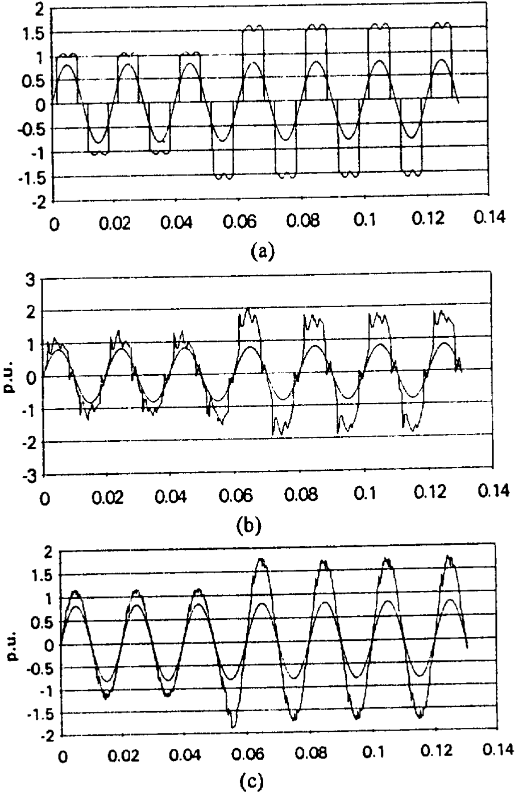


Fig. 13. Simulated results for transient operating conditions. (a) The load current. (b) The line current after the first inverter and the respective phase to neutral voltage. (c) The power system line current and the phase to neutral voltage.

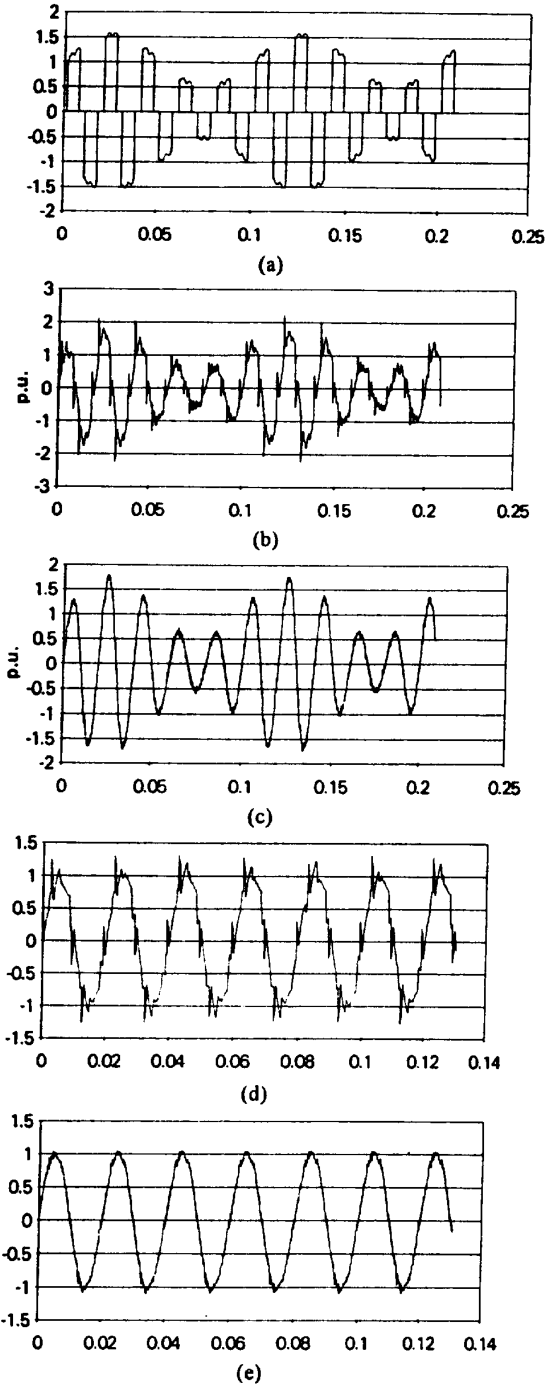


Fig. 14. Simulated results for compensation of a 10 Hz load current fluctuation. (a) The fluctuating nonlinear load current. (b) Power system current between the two inverters for compensation with a reference signal generated with a low pass filter tuned at 150 Hz. (d) Power system current between the two inverters for compensation with a reference signal generated with a low pass filter tuned at 5 Hz. (e) Power system current for compensation with a reference signal generated with a low pass filter tuned at 5 Hz.

CONCLUSION

An active power filter implemented with two PWM voltage-source inverters connected in cascade was presented and analyzed in this paper. The proposed active power filter is aimed toward application that require displacement power factor correction and current harmonics compensation. The reference signals required by the active power filter were obtained by using the instantaneous reactive power concept. Current control was implemented with a vector control technique. Each converter was operated at a different switching frequency, allowing the compensation of high power nonlinear loads. Simulated results has demonstrated the operating performance of the proposed active power filter system.

ACKNOWLEDGEMENT

The authors would like to acknowledge the finance support from FONDECyt through the project 92-0262. Also the authors would like to thank the Dirección of Investigación of Universidad de Concepción, the International Copper Association, nd the Agency for International Development for the assistance gave through the projects # 20.92.11, ICA # 416, AID # 11.196.

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