

A Three-Phase Active Power Filter Implemented With Multiples Single-Phase Inverter Modules In Series

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Abstract- An active power filter implemented with multiples single-phase full bridge voltage source inverters is presented and analyzed in this paper. The proposed active power filter is aimed to compensate displacement power factor and current harmonic components in high voltage power distribution systems. A control scheme is developed to allow the operation of the inverter modules at different voltages and switching frequencies. Simulated waveforms for steady state and transient operating conditions shows the compensation characteristics of the proposed topology.

I. INTRODUCTION

ACTIVE power filters have proved to be an interesting and effective solution to compensate current harmonics and reactive power in power distribution systems [1], [2], [3]. Although many papers have been published in this subject during the last decade, most of them dealt with their principles of operation, design of the control schemes, and the presentation of different techniques to calculate the reference signals required by the control scheme [4], [5]. In order to achieve higher power level, hybrid topologies that combines active and passive compensation techniques have been developed [5].

In the last years the development of high voltage converters have attracted the attention of power electronic engineers, specially for motor drive applications. Multilevel voltage-source inverters and multi cells converters [6], [7], seem to be the standard solution for medium voltage motor drive applications. Multilevel cascade or multi cells inverters have also been proposed for the construction of high voltage compensators [10] – [15], basically using identical voltage cells operating at equal voltage dc buses. The binary inverter proposed in this paper as been used only as static var generator [15].

This paper presents an active power filter implemented with multiple single-phase voltage-source inverter connected in series (fig. 1), in binary configuration. Each single-phase voltage-source inverter is composed by a dc capacitor and a full-bridge single-phase pulse-width-modulated voltage-source inverter. With this type of topology higher voltage levels can be achieved, which makes the proposed topology suitable for compensation of medium and high voltage power distribution systems. A three-phase power distribution transformer is

recommended for isolation and to be used as a link reactor, X_L , (fig. 1).

Each power cell can be operated at different dc voltage and switching frequency improving the converter efficiency and compensation characteristics. A new and simple control scheme is presented for the correct operation of each power cell and to satisfy compensation requirements. The current reference required by each cell can be easily obtained allowing the generation of the total compensating current, and the absorption of the required active power to compensate converter losses and to keep the dc voltage constant.

Simulated results for steady-state and transient operating conditions prove the compensation capabilities of the proposed scheme.

II. PRINCIPLES OF OPERATION

The active power filter topology proposed in this paper is shown in fig. 1, as binary multilevel inverter. Each self-controlled power cell is connected in series to the power distribution system through a coupling transformer or reactor. Compared to the Robicon structure [6], each power cell does not require a rectifier, since the dc voltage can be controlled directly from the inverter. For this reason, the proposed converter topology does not require a special transformer with multiple secondary windings. The active power filter is implemented with two single-phase full-bridge PWM-VSI per phase. Each converter operates at different voltage and switching frequency. The converter with a higher dc voltage operates at lower switching frequency and compensates only the reactive power and the low frequency current harmonics. The second converter operates at higher switching frequency and generates the high frequency current harmonics. This mode of operation presents better performance and compensation characteristics than the scheme in which each converter operates at the same dc voltage and constant switching frequency [9].

A. Inverter Modulation Technique

The modulation scheme proposed keeps a low switching frequency in the higher voltage cell by using a staircase

modulation technique. The lower voltage cell is switched at a constant higher frequency with a synchronized carrier based PWM scheme [8].

The staircase modulation for the higher voltage cell is based on the instantaneous value of the desired output voltage, u . If u is higher than $+V_{DC}$ (DC voltage of the lower voltage cell), the higher voltage cell output u_{HVcell} goes to $+2V_{DC}$; but if u is lower than $-V_{DC}$, then u_{HVcell} goes to $-2V_{DC}$; in other case u_{HVcell} remains in 0. The lower voltage cell output u_{LVcell} is easily obtained from the subtraction $u - u_{HVcell}$. Table 1 shows the modulation scheme and figures 2 and 3 show the voltage output signals using the proposed modulation scheme with two different references: one sinusoidal and the other distorted with 5th, 7th, 11th and 13th harmonics. Figure 3 shows that the inverter is able to deliver harmonic voltages that will generate the compensating currents for active power filter application.

This modulation scheme allows to operate both cells with different switching frequencies, compensating the displacement power factor and the dominant low current harmonics with the slowest inverter and leaving the higher frequencies current harmonics to be compensated with the faster converter.

Since the inverter cells are connected in series, the total compensating current circulates through both converters. This topology requires a special signal reference generator scheme to obtain the required compensating current. Compared to shunt active power filters implemented with conventional three phase two level inverters, the proposed scheme operates with voltage reference signals for each inverter cell, instead of current references. In this topology, the variable that must be controlled in each converter is the output voltage, but also the control of both ac current and dc voltage in each cell is required. For this reason, in this application a de-coupled control strategy is the best suited approach.

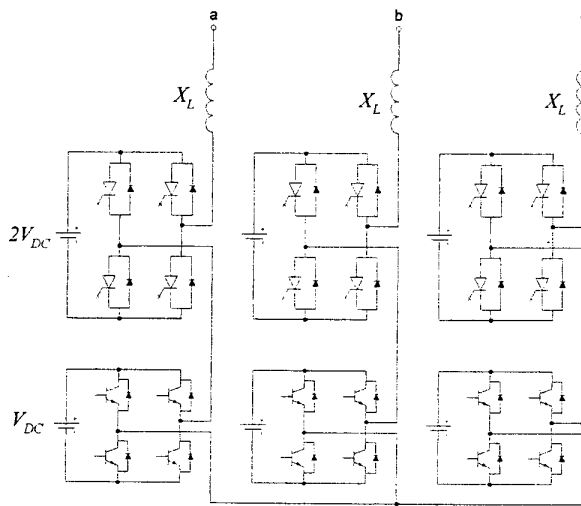


Figure 1. The proposed active power filter topology implemented with two single-phase power cells per phase.

TABLE I
MODULATION SCHEME

Desired output (u) between	High voltage cell output	Low voltage cell output
$-3 V_{DC}$ and $-2 V_{DC}$	$-2 V_{DC}$	$0 \leftrightarrow -V_{DC}$
$-2 V_{DC}$ and $-V_{DC}$	$-2 V_{DC}$	$0 \leftrightarrow +V_{DC}$
$-V_{DC}$ and 0	0	$0 \leftrightarrow -V_{DC}$
0 and $+V_{DC}$	0	$0 \leftrightarrow +V_{DC}$
$+V_{DC}$ and $+2V_{DC}$	$+2 V_{DC}$	$0 \leftrightarrow -V_{DC}$
$+2 V_{DC}$ and $+3 V_{DC}$	$+2 V_{DC}$	$0 \leftrightarrow +V_{DC}$

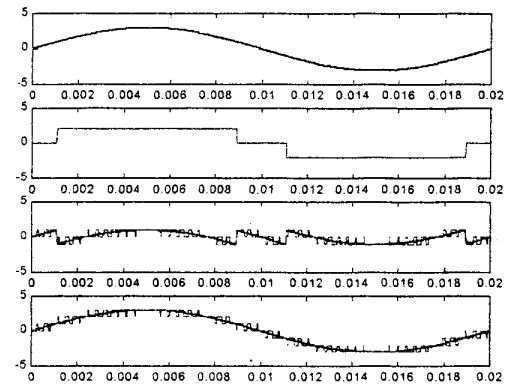


Figure 2. Output voltage waveforms using a sinusoidal reference. (a) Desired output waveform. (b) Higher voltage cell output. (c) Lower voltage cell output. (d) Generated and desired output voltage.

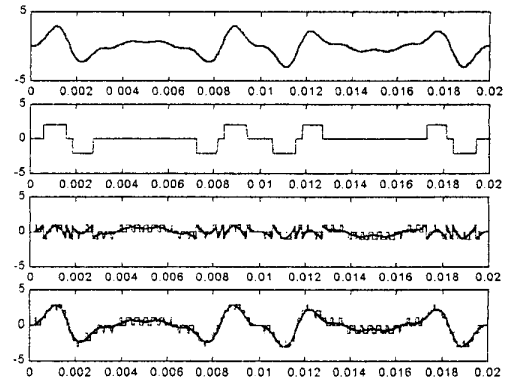


Figure 3. Output voltage waveforms using a distorted reference. (a) Desired output waveform. (b) Higher voltage cell output. (c) Lower voltage cell output with the modulator waveform. (d) Generated and desired output voltage.

The voltage and current control loops are designed based on the time response requirements of the active power filter. Since the current control loop defines this time response, it has to be fast enough to follow closely the reference waveform. Instead, the dc voltage control loop does not need to be fast and can be selected to be much slower than the current control loop. In this way each power cell has two de-coupled control systems which

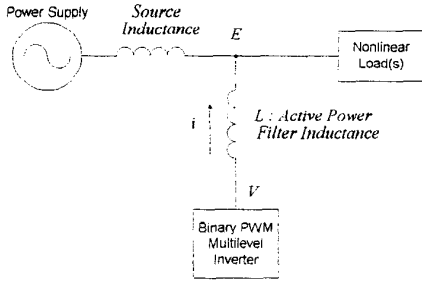


Figure 7. Single-phase equivalent circuit of the proposed active power filter connected to the power system.

$$V = L \frac{di}{dt} + E \quad (1)$$

The design of the reactor is performed with the constraint that for a given switching frequency the maximum slope of the inductor current must be smaller than the slope of the inductor of the triangular that defines the switching frequency. In this way, the intersection between the current error signal and the triangular waveform will always exist.

The slope of the triangular waveform used to modulate the faster (lower voltage) converter, λ , is defined by

$$\lambda = 4\xi f_i \quad (2)$$

where ξ is the amplitude of the triangular waveform, which as to be equal to the maximum permitted amount of ripple current, and f_i is the frequency of the triangular waveform, this is, the faster inverter switching frequency. The maximum slope of the inductor current is equal to

$$\frac{di}{dt} = \frac{V - E}{L} \quad (3)$$

Since the slope of the inductor current has to be smaller than the slope of the triangular waveform, from (2) and (3),

$$L = \frac{V - E}{4\xi f_i} \quad (4)$$

Where V is the inverter output voltage, E is the ac source voltage, ξ is the amplitude of the current ripple and f_i is the maximum switching frequency.

B. DC Capacitors

One of the selection criteria used to calculate the value of the converter capacitance C is related to the maximum voltage fluctuation allowed in the dc bus when transient changes in the load currents occur. In this case, the value of C is obtained from the following equation:

$$C = \frac{1}{\Delta V} \int i_C(t) dt \quad (5)$$

where $i_C(t)$ is the instantaneous current flowing through the dc capacitor and ΔV is the voltage fluctuation allowed in the dc bus. Equation (5) gives the value of the dc capacitor that will maintain the dc voltage fluctuation below ΔV p.u. The instantaneous value of the dc current is defined by the product of the inverter line currents with the respective switching functions. The mean value of the dc current that generates the maximum overvoltage can be estimated by

$$\int i_C(t) dt = I \int [\sin(\omega t) + \sin(\omega t + 120^\circ)] dt \quad (6)$$

In this expression the inverter ac current is assumed to be sinusoidal. These operating conditions represent the worst case.

IV. SIMULATED RESULTS

A. Steady state operation

The steady state performance of the proposed active power filter structure was checked by computer simulation. For a simple power system topology, consisting of a voltage source and a nonlinear load, the compensation characteristics and the associated frequency spectrum of the respective current waveforms are illustrated in figure 8. Figure 9 illustrates the output voltage of each converter with their respective frequency spectrum. Figure 10 shows the compensating current generated by the proposed active power filter with the respective reference signal. The THD of the system current without filtering is 28,67%, and by connecting the active power filter, the system line current THD is significantly reduced to 4.03%.

B. Transient condition: step change in the load current

A transient operating condition is obtained by generating a step change in the firing angle of the three-phase controlled rectifier from $\alpha = 45^\circ$ to $\alpha = 15^\circ$. Figure 11(a) shows the transient step change in the load current and in the power factor. In figure 11(b), the current reference and the actual inverter output current is shown. Figure 11(c) shows the ac mains phase-to-neutral source voltage with the respective line current. This figure shows the effectiveness of the active power filter, since it is able to keep the current in phase with the phase-to-neutral voltage, keeping the ac source power factor equal to one and eliminating low-frequency current harmonics. Finally, figure 11(d) shows the voltage across the dc capacitors for both converters.

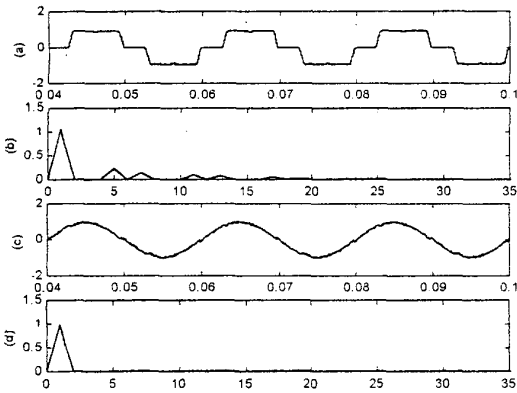


Figure 8. Simulated system current waveform and frequency spectrum. (a) System current waveform without filter. (b) Frequency spectrum of the system current without filter. (c) System current waveform with active power filter. (d) Frequency spectrum of the system current with active power filter.

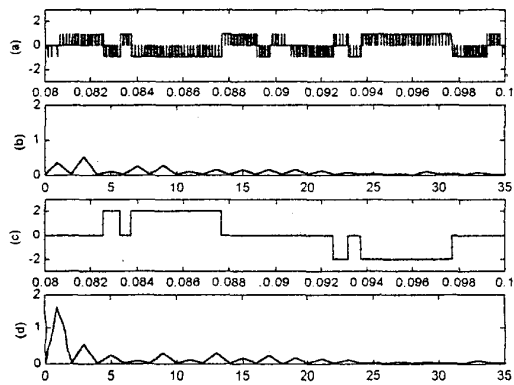


Figure 9. Simulated waveforms of the inverter output voltages and respective frequency spectrum. (a) Output voltage of the faster (lower voltage) converter. (b) respective frequency spectrum. (c) Output voltage of the slower (higher voltage) converter. (d) respective frequency spectrum.

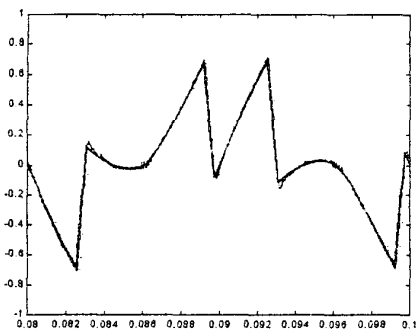


Figure 10. Simulated compensated current: current reference signal and active filter output current.

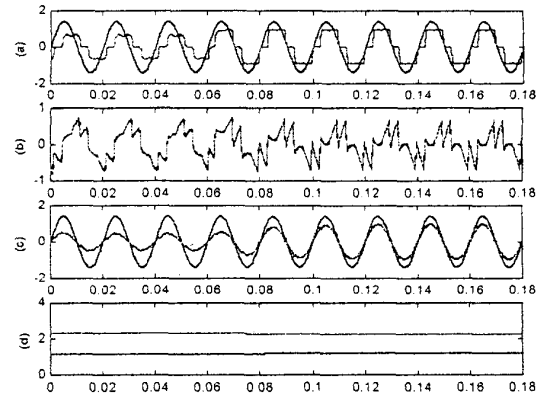


Figure 11. Simulated results for transient operating conditions. (a) The phase-to-neutral source voltage and the load current. (b) Inverter ac output current and its reference. (c) Phase-to-neutral source voltage and the ac mains line current. (d) Voltage across the dc capacitors in both converters.

V. CONCLUSION

An active power filter implemented with a binary seven-level inverter has been presented and analyzed. The principal advantage of the proposed scheme is its straightforward application in high voltage power distribution systems. A simple control scheme is developed to obtain the desired operating response of the active power filter. The proposed topology was verified by computer simulation, by compensating power factor and current harmonics injected by a current source rectifier in steady state and under transient conditions.

VI. ACKNOWLEDGMENT

The authors would like to thank FONDECYT for the financial support given through project #1990413.

VII. REFERENCES

- [1] B. Singh, K. Al-Haddad, A. Chandra, "A Review of Active Power for Quality Improvement", *IEEE Trans. On Industry Electronics*, vol. 46, n° 5, Oct. 1999, pp. 960-971.
- [2] W.M. Grady, M.J. Samotyj, A.H. Noyola, "Survey of Active Power Line Conditioning Methodologies," *IEEE Trans. on Power Delivery*, vol. 5, July 1990, pp. 1536-1542.
- [3] H. Akagi, "Trends in Active Power Line Conditioners," *IEEE Trans. on Power Electronics*, vol. 9, pp. 263-268, May 1994.
- [4] H. Akagi, A. Nabae, S. Atoh, "Control Strategy of Active Power Filters Using Multiple Voltage-Source PWM Converters," *IEEE Trans. on Ind. Applications*, vol. IA-22, n° 3, pp. 460-465, May/June 1986.
- [5] F.Z. Peng, H. Akagi, A. Nabae, "A New Approach to harmonic Compensation in Power Systems," in *Conf. Record IEEE-IAS Annual Meeting*, 1988, pp. 874-880
- [6] P.W. Hammond, "A New Approach to Enhance Power Quality for Medium Voltage AC Drives," *IEEE Trans. on Ind. Applications*, vol. 33, n° 1, Jan./Feb. 1997, pp. 202-208.
- [7] A. Nabae, I. Takahashi, H. Akagi, "A New Neutral-Point Clamped PWM Inverter," *IEEE Trans. in Ind. Applications*, vol. IA-17, n° 5, Sept./Oct. 1981, pp. 518-523.

- [8] R. Lund, M. Manjrekar, P. Steimer, T.A. Lipo, "Control Strategies for an Hybrid Seven-Level Inverter," *IEEE EPE Conference Proceedings*, 1999.
- [9] L.A. Morán, L. Fernández, J.W. Dixon, "A Simple and Low – Cost Control Strategy for Active Power Filters Connected in Cascade", *IEEE Trans. in Ind. Electronics*, vol. 44, nº 5, Oct. 1997, pp. 621-628.
- [10] F.Z. Peng, J.S Lai, J.W. McKeever and J. VanCoevering, "A Multilevel Voltage-Source Inverter with Separate DC Sources for Static Var Generation", *IEEE Trans. on Industry Applications*, Vol.32, No.5, September/October 1996, pp. 1130-1138.
- [11] F.Z. Peng and J.S Lai, "Dynamic Performance and Control of a Static Var Generator Using Cascade Multilevel Inverters", *IEEE Trans. on Industry Applications*, Vol.33, No.3, May/June 1997, pp. 748-755.
- [12] G. Joos, X. Huang and B.T. Ooi, "Direct-Coupled Multilevel Cascaded Series Var Compensators", *IEEE Trans. on Industry Applications*, Vol.34, No.5, September/October 1998, pp. 1156-1163.
- [13] F.Z. Peng, J.W. McKeever and D.J. Adams, "A Power Line Conditioner Using Cascade Multilevel Inverters for Distribution Systems", *IEEE Trans. on Industry Applications*, Vol.34, No.6, November/December 1998, pp. 1293-1298.
- [14] Y. Liang and C.O. Nwankpa, "A New Type of STATCOM Based on Cascading Voltage-Source Inverters with Phase-Shifted Unipolar SPWM", *IEEE Trans. on Industry Applications*, Vol.35, No.5, September/October 1999, pp. 1118-1123.
- [15] K.V. Patil, R.M. Mathur, J. Jiang and S.H. Hosseini, "Distribution System Compensation using a new Binary Multilevel Voltage-Source Inverter", *IEEE Trans. on Power Delivery*, Vol.14, No.2, April 1999, pp. 459-464.