

ANALYSIS AND EVALUATION OF DIFFERENT MODULATION TECHNIQUES FOR ACTIVE POWER FILTERS

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Abstract - The effectiveness of an active power filter depends basically on three characteristics: a) the design characteristics of the PWM modulator, b) the method implemented to generate the reference template and c) the modulation method used. For the last characteristic there are many methods, most of them based on PWM strategies. In this paper, three of these methods, whose characteristics are their simplicity, are analyzed: Periodical Sampling Control, Hysteresis Band Control, and Triangular Carrier Control. These three methods have been tested with different waveform templates: sinusoidal, quasi-square and rectifier compensation current. The paper shows that, depending on the type of current the active filter has to follow, one strategy may be better than the others. The analysis is based on using the same switching frequency and the results are compared through a THD method which takes into account the particular shape of the waveform template. Simulations and experimental results are presented in the paper.

I. INTRODUCTION

Active power filters play an important role in reducing harmonic contamination in power lines [1]. In the past twenty years, the proliferation of nonlinear loads such as static power converters, arc furnaces and others, have resulted in a variety of undesirable phenomena in the operation of power systems, which in many cases cannot be solved with passive LC filters. The basic difference between LC filters and active filters is that the active filters have the capability to compensate randomly varying currents.

One of the most popular principles of operation used to implement topologies for active power filters is the "Shunt Active Power Filter" [2,3], shown in Fig. 1. A current source is connected in parallel with the nonlinear load and controlled to generate the harmonic currents needed for the load. In this form, the mains only needs to generate the fundamental current, avoiding contamination problems along the power line.

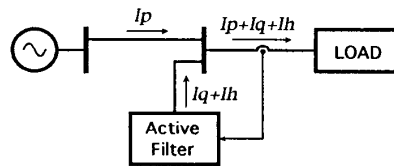


Fig. 1. Interconnection of active filter and load.

The Fig. 2 shows in more detail the type of active filter being analyzed. This kind of active filter can follow almost any waveform template with different grades of accuracy. The accuracy will depend on the current waveform the filter has to follow, the parameters of the filter and the PWM strategy. Previous works [4-8] have shown partial results related to harmonic distortion and modulation methods but none of them makes an analysis to compare the results obtained.

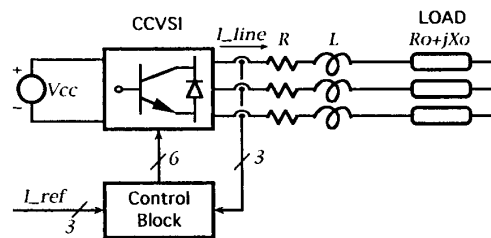


Fig. 2. Block diagram of the active filter.

II. ANALYSIS OF THE PWM GENERATORS

A. Description of the Modulation Methods

In this paper three different methods of modulation are analyzed: Periodical Sampling (PS), Hysteresis Band (HB), and Triangular Carrier (TC).

The Periodical Sampling method switches the power transistors of the active filter during the transitions of a square wave clock of fixed frequency: the sampling frequency. As shown in Fig. 3a, this type of control is very simple to implement: only a comparator and a D-type flip-flop are needed per phase. The main advantage of this method is that the minimum time between switching transitions is limited to the period of the sampling clock [6]. However, the switching frequency itself is not clearly defined.

The Hysteresis Band method switches the transistors when the error exceeds a fixed magnitude: the hysteresis band. As it can be seen in Fig. 3b, this type of control needs a single comparator with hysteresis per phase. In this case the switching frequency is not determined, but it can be estimated from [7].

The Triangular Carrier method, shown in Fig. 3c, compares the output current error with a fixed amplitude and frequency triangular wave: the triangular carrier. The error is processed through a proportional-integral (PI) gain stage before the comparison with the triangular carrier takes place. As it can be seen, this control scheme is more complex than PS and HB. The values used for the proportional and integral constants were chosen according to [8], which works well for sinusoidal waveform under steady-state. The rule is the following: K_p is set to unity; then the amplitude of the carrier is set such that the carrier slope equals the highest di/dt allowed in the system (determined by V_{cc} , V_{load} and L); finally, K_i is set equal to the frequency of the triangular carrier. For other waveforms, the TC works better with $K_i=0$, because K_i

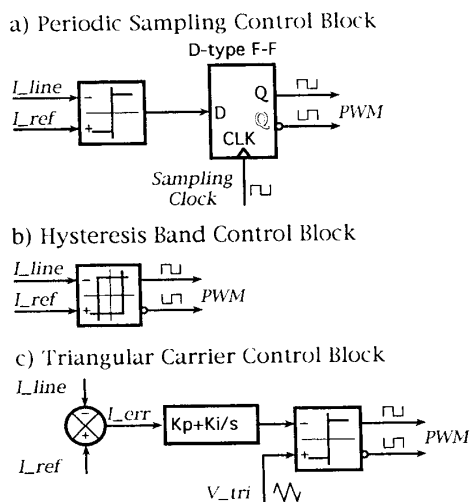


Fig. 3. Modulation control blocks. (a) Periodical sampling. (b) Hysteresis band. (c) Triangular carrier

affects the transient response. In the TC method the switching frequency is usually the carrier frequency or near. However this method can generate short duration commutations which may need to be inhibited when using slow turn-off transistors.

B. Reference Waveforms Under Study

The control methods are tested with three different waveforms: i) Sinusoidal Current Waveform (SCW), ii) Quasi-Square Current Waveform (QSCW), and iii) six-pulse Rectifier Compensation Current Waveform (RCCW). Fig. 4 shows these waveforms for a 50 Hz fundamental frequency. Because active filters cannot generate an infinite slope current (di/dt), the maximum slope of the waveforms are limited to the maximum di/dt imposed by the load. This permits a better comparison of the control methods.

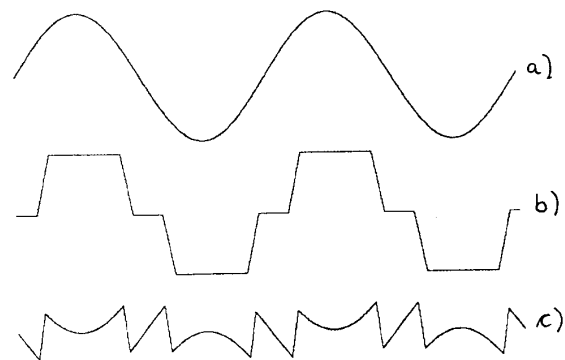


Fig. 4. Reference waveforms. (a) Sinusoidal current waveform. (b) Quasi-square current waveform. (c) Compensation current for six-pulse rectifier.

The SCW is used in power factor correction and machine drives. In power factor correction the active filter generates a phase shifted sinusoidal current to set the desired power factor. In machine drives sinusoidal currents are used for driving synchronous and induction motors. In the experiments and simulations a 10 A peak reference current was used, which corresponds to an effective current near to 7 A.

The QSCW finds application in driving brushless DC motors. Due to its stepping shape this waveform is well suited for comparing the transient response of the different control methods. A 10 A peak QSCW was used for the experiments and simulations, corresponding to an effective current near to 8 A.

The RCCW is a typical current waveform for an active filter feeding a six-pulse rectifier load. This waveform contains only harmonics of the fundamental, but not the fundamental itself. In the experiments and simulations a 5 A peak RCCW was used, corresponding to an effective current near to 2.5 A.

C. Comparison of the Control Methods

The control methods are compared at the same switching frequency, which corresponds to similar losses and similar speed switching devices. This permits a direct comparison on how efficient in terms of low distortion these control methods are.

In order to measure the level of distortion (or undesired harmonic generation) introduced by the control methods under study, equation (1) is defined:

$$\% \text{Distortion} = \frac{100}{I_{rms}} \sqrt{\frac{1}{T} \int_T (i_{line} - i_{ref})^2 dt} \quad (1)$$

In (1), the term I_{rms} is the effective value of the desired current. The term inside the square root gives the rms value of the error current, which is undesired. This formula measures the percentage of error (or distortion) of the generated waveform. This definition is independent of the reference waveform, being a good choice for comparing the performance of active filters. In the case of a sinusoidal reference current, this formula is equivalent to THD.

III. ACTIVE FILTER SIMULATIONS

The simulations are based on the active filter presented in Fig. 2. The dc voltage was set to 200 V. The values of R, R_o , L and L_o (X_o 's inductance at 50 Hz) were 0.5 ohm, 1.5 ohm, 5 mH and 8 mH respectively. This gives a total series R_s and L_s of 2 ohm and 13 mH respectively.

A. Simulations With Sinusoidal Current Waveforms

In Fig. 5 the methods under study are compared in terms of distortion versus switching frequency, using a sinusoidal waveform reference. It can be seen that TC and HB are superior to PS.

Fig. 6 shows the current waveforms generated by the three control methods for a switching frequency of 1.5 kHz. It can be seen that for PS control the generated current does not swing symmetrically around the

reference; instead it has a constant DC error. In HB the generated current oscillates symmetrically around the reference with the consequent smaller distortion than PS. The current waveform generated by TC method is similar to HB but with lower ripple.

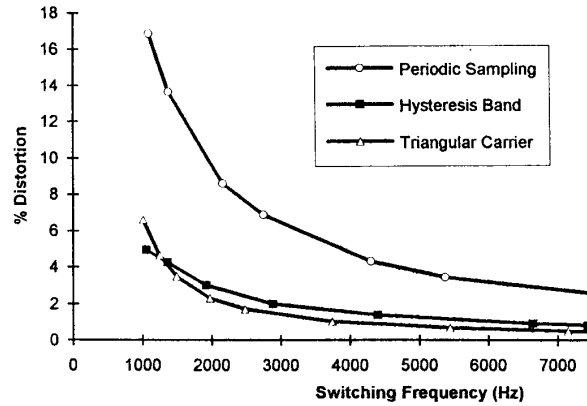


Fig. 5. Distortion comparison for sinusoidal reference.

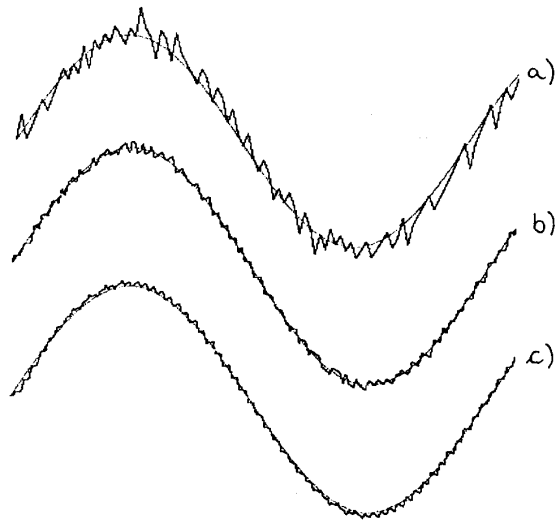


Fig. 6. Waveforms obtained using 1.5 kHz switching frequency. (a) PS method. (b) HB method. (c) TC method.

In Fig. 7 the frequency spectra generated for a switching frequency of 1.5 kHz are shown. As it can be seen, the spectrum of PS is not clearly related to the switching frequency and contains odd and even harmonics. The spectrum of the HB resembles to the PS, however the harmonics are of lower magnitude. Finally, the spectrum of the TC method is concentrated in two sidebands (28th and 32th harmonics) around the 30th harmonic (which

corresponds to the 1.5 kHz carrier frequency). The other harmonics are of a much lower amplitude. TC is very useful where a single fixed frequency is to be produced, because a pair of passive filters can be added to the system eliminating these sidebands.

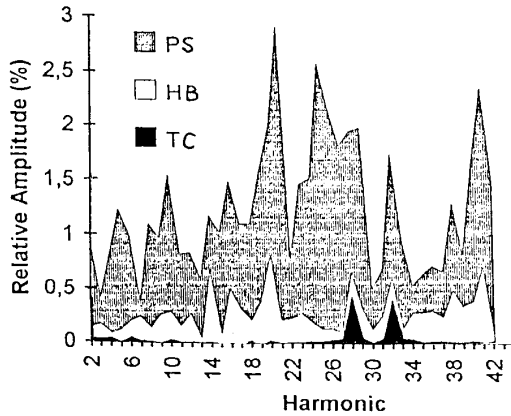


Fig. 7. Frequency spectra comparison for SCW, using 1.5 kHz switching frequency.

B. Simulations With Quasi-Square Current Waveforms

The transient response of an active filter intended to compensate dynamic loads is very important. The QSCW is useful to test the transient response of the methods under study.

In Fig. 8 the percentage of distortion generated by the three methods is shown. In this case the best method is HB due to its excellent transient response. In the case of TC, it can be stated that the permanent error term, due to the only proportional gain used in the controller, puts TC in third place, but very close to PS method.

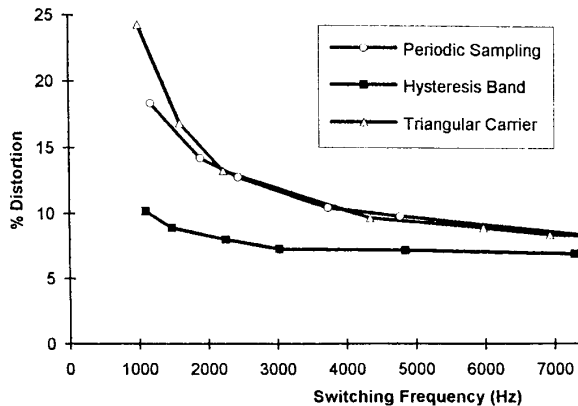


Fig. 8. Distortion comparison for QSCW reference.

The Fig. 9 shows the waveforms generated with the three control methods using a switching frequency of 2 kHz. As it can be seen, these figures are in agreement with the results obtained in Fig. 8.

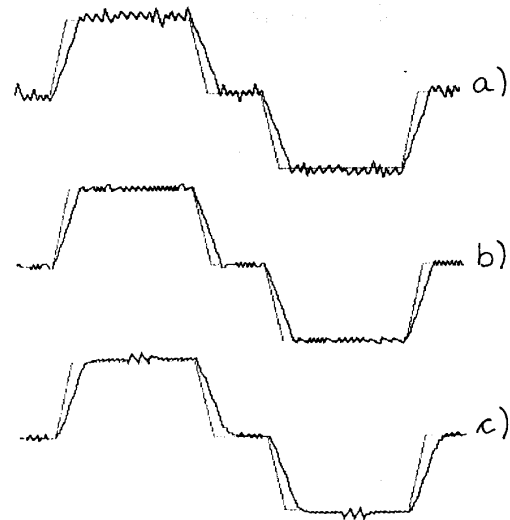


Fig. 9. Waveforms obtained with 2 kHz switching frequency. (a) PS method. (b) HB method. (c) TC method.

C. Simulations With Rectifier Compensation Current

In Fig. 10 the curves obtained for a RCCW reference are shown. In this case HB method is again the best, followed by PS and TC. On the other hand, the Fig. 10 also shows that TC method could perform better than PS under low switching frequencies. The Fig. 11 shows the waveforms obtained for a 2 kHz switching frequency, using the three methods of modulation.

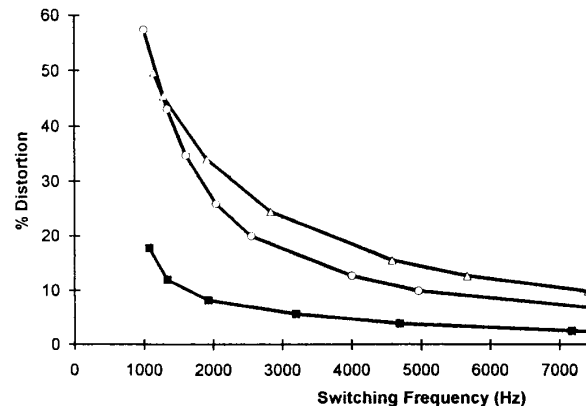


Fig. 10. Distortion comparison for RCCW reference.

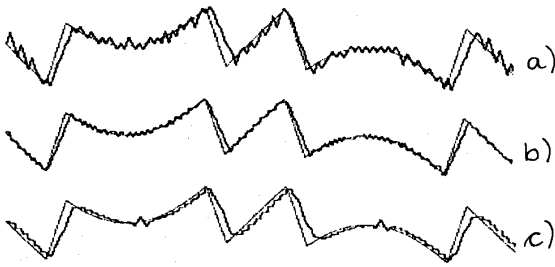


Fig. 11. Waveforms obtained with 2 kHz switching frequency. (a) TC method. (b) HB method. (c) PS method.

D. Switching Time Delay Effects

The simulations of points *A*, *B*, and *C* did not take into account time delays present in driver circuits and turn-on and turn-off times of the transistors. For instance, an optocoupled driver has a typical delay of 10 μ s. Adding to the driver delay, a power transistor can have a total turn-off time ranging from a few μ s for medium power MOSFETs to as long as 100 μ s for high current bipolar devices.

To illustrate the effect of the delays associated with the inverter, a representative total delay of 40 μ s will be considered. Figs. 12, 13 and 14 compare the performance of the PS, HB and TC methods, respectively, for a sinusoidal current reference.

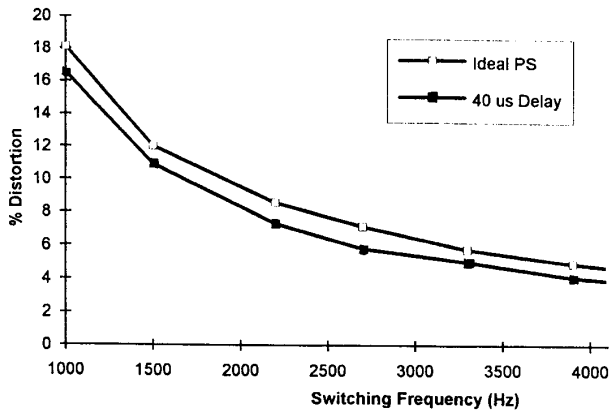


Fig. 12. Distortion comparison for PS with 40 μ s switching delay.

As shown in Fig. 12, PS seems to benefit from time delays. This is explained by the fact that a time delay makes the current swing around the reference, instead of being above it or below it most of the time. By contrast, the HB method deteriorates with time delays, having a higher distortion, as shown in Fig. 13. This is because the delays make the transistors switch outside the hysteresis

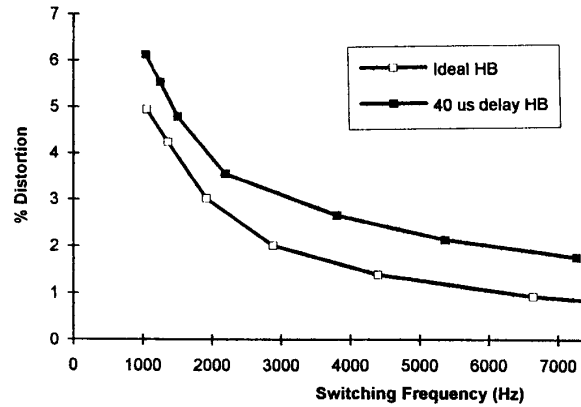


Fig. 13. Distortion comparison for HB with 40 μ s switching delay.

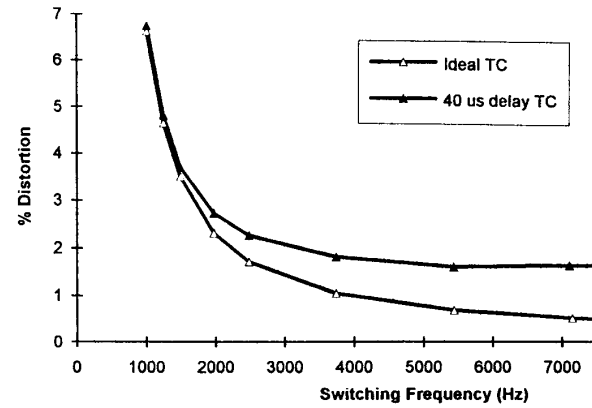


Fig. 14. Distortion comparison for TC with 40 μ s switching delay.

band limits, increasing the current ripple, even after reducing the band to keep the switching frequency constant. Finally the TC method is clearly affected by the 40 μ s delay, as shown in Fig. 14. It can be noted that this effect is more important at higher commutation frequencies.

Fig. 15 shows the waveforms obtained with SCW reference at 1.5 kHz switching frequency, using the three control methods including the 40 μ s time delay. As it can be noticed by comparing Fig. 6a, 6b and 6c with Fig. 15a, 15b and 15c respectively, they agree with the results displayed in Figs. 12, 13 and 14.

Fig. 16 and 17 show the waveforms obtained with QSCW and RCCW respectively, at 2 kHz switching frequency using the three control methods, including the 40 μ s time delay. These Figs. can be compared with Figs. 9 and 11 respectively.

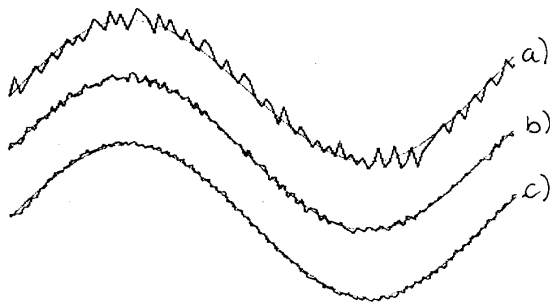


Fig. 15. Waveforms obtained using SCW at 1.5 kHz switching frequency and 40 us time delay. (a) PS method. (b) HB method. (c) TC method.

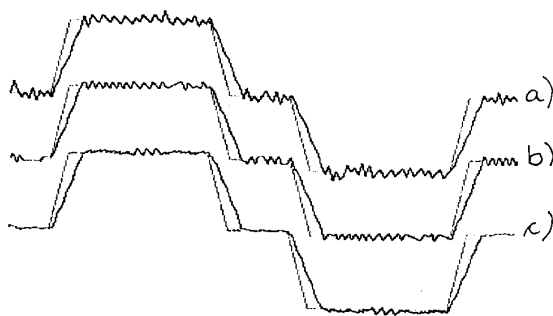


Fig. 16. Waveforms obtained using QSCW at 2 kHz switching frequency and 40 us time delay. (a) PS method. (b) HB method. (c) TC method.

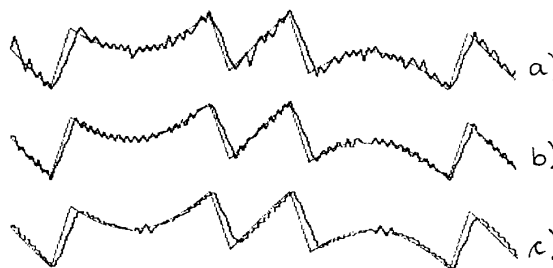


Fig. 17. Waveforms obtained using RCCW at 2 kHz switching frequency and 40 us time delay. (a) PS method. (b) HB method. (c) TC method.

IV. EXPERIMENTAL RESULTS

The experimental results were taken in a 2 kVA current controlled voltage source inverter, shown in Fig. 2. The dc supply is 200 V, the total series inductance L_s is 13 mH, the total series resistance R_s is 2 ohm, and the time delays associated to the driving circuitry and transistor turn-off delays are about 40 us.

In figures 18, 19 and 20, real current waveforms obtained from the three control methods are shown (Periodic Sampling, Hysteresis Band and Triangular Carrier).

Fig. 18 shows the waveforms obtained with sinusoidal reference using a switching frequency of 1.5 kHz. For this case the TC method is the best, followed by HB.

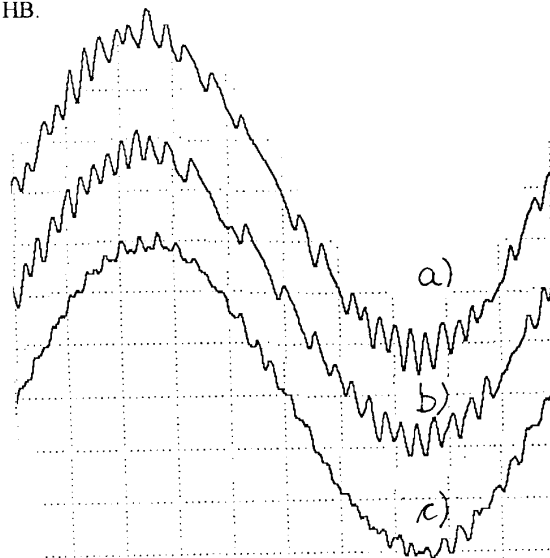


Fig. 18. Experimental results for sinusoidal reference at 1.5 kHz switching frequency. (a) Periodical sampling. (b) Hysteresis band. (c) Triangular carrier.

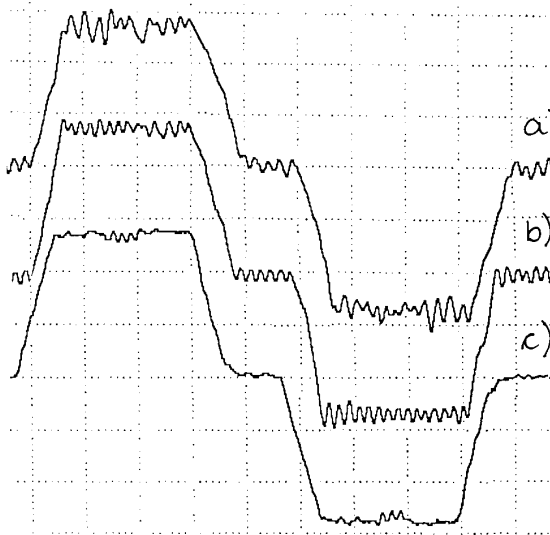


Fig. 19. Experimental results for quasi-square current reference at 2 kHz switching frequency. (a) Periodical sampling. (b) Hysteresis band. (c) Triangular carrier.

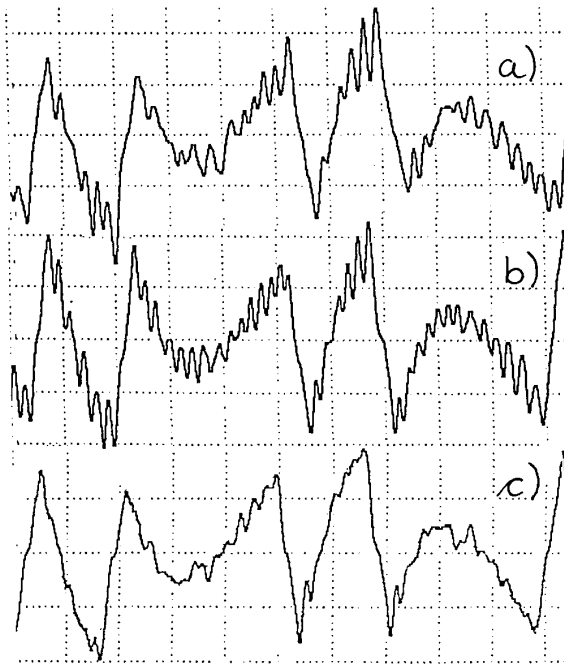


Fig. 20. Experimental results for six-pulse rectifier compensating current at 2 kHz switching frequency. (a) Periodical sampling. (b) Hysteresis band. (c) Triangular carrier.

CONCLUSIONS

Three different methods of current modulation to control active power filters have been implemented and evaluated, using three different current reference waveforms: sinusoidal, quasi-square and rectifier compensating current. The methods of modulation used to follow these references were: Periodical Sampling (PS), Hysteresis Band (HB) and Triangular Carrier (TC).

From the results obtained, and based on the particular conditions in which the simulations and experiments were performed, the following can be concluded:

- (1) The results show that the methods of modulation tested are affected by time delays, generated in the driving circuitry and the turn-on and turn-off time of the power transistors. In particular, the Periodic Sampling Method, seems to improve by the addition of time delays, Hysteresis Band Method deteriorates and the last method of modulation tested, the Triangular Carrier Method also deteriorates.
- (2) For sinusoidal current reference waveforms, the triangular carrier Method (TC), using PI control to adjust the current error, has shown to be the best of

the three under study. On the other hand, the Hysteresis Band Method (HB) showed better performance than the others to follow the two non-sinusoidal waveforms. As Periodical Sampling Method (PS) improves with time delays and HB deteriorates, it seems possible to think that active filters, with very slow power switches, could perform better with PS than with HB. However, further investigation has to be performed to ensure the validity of this statement.

ACKNOWLEDGMENTS

The authors want to thank the "Fondo de Desarrollo Científico y Tecnológico", FONDECYT, through the project number 262-92, for the financial support which makes it possible to do this research.

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