

Control schemes for shunt active filters to mitigate harmonics injected by inverted-fed motors

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Abstract—This paper discusses the performance of different current control schemes used in shunt active power filters. The controller schemes are linear PI regulator, hysteresis control, and a regulator based on the dead-beat controller. The feasibility of the three control schemes have been tested with different waveform and the results are compared through the mean error and root mean square error between the current active filter and the reference current and the total harmonic distortion of both currents. Finally, the modified dead beat controller is applied to a shunt active filter designed for mitigating harmonics injected by an adjustable speed drive.

Index Terms—VSI Control, active filter, Power quality, ASD.

I. INTRODUCTION

Nowadays, with the wide application of the non linear loads and electronic equipment in distribution systems such as Adjustable Speed Drives (ASD), the problem of power quality has become increasingly serious. Control of harmonics perturbations by passive filters can generate additional resonance problems. This has lead to the development of active filters for harmonic compensation and active damping of harmonic resonance.

Active filters are devices designed to improve the power quality in distribution networks. In order to reduce the injection of non-sinusoidal load currents, shunt active filters can be connected in parallel to the disturbing loads. Its main component is a Voltage Source Inverter (VSI) with a dc bus capacitor. The VSI is connected to the point of common coupling (PCC) via the leakage inductance of a transformer.

The purpose of the active filter is to compensate distorted current drawn by the non-linear loads from the utility grid, so that only the fundamental frequency components remain in the grid current. The active filter and its current control must accurately track the sudden slope variations in the reference current.

The choice and implementation of the current regulator is one of the more critical issues for the achievement of a satisfactory performance level. Three major classes of current control techniques have been developed over last decades: linear PI control, digital deadbeat control and hysteresis control [1], [2], [3], [4]. In this paper, a comparison among the three control performance is done and the best one is tested in a shunt active filter designed for mitigating harmonics generated by an ASD.

The organization of the paper is as follows. Section II presents

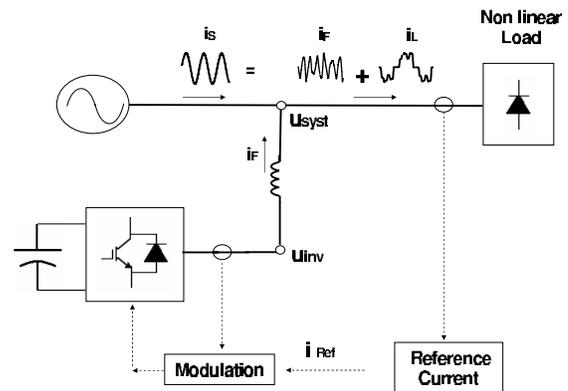


Fig. 1. Shunt active filter.

the principle of operation of the three control schemes. In section III, the comparison among the three current control techniques is discussed. Section IV presents the performance of the shunt active filter for mitigating harmonics injected by ASD and finally conclusions are drawn in section V.

II. CURRENT CONTROL SCHEMES

The aim of the controller is to determine the switching actions of the inverter such that the desired current reference is exactly followed. In this paper, the current control schemes considered are linear current control, digital controller based on deadbeat regulator and current controllers based on delta modulation (DM). It is assumed that the source, $u_{syst}(t)$, is balanced, sinusoidal with frequency ω , the shunt active power filter operates as a controlled voltage source, $u_{inv}(t)$, and is connected to the PCC via an inductance, L , that takes into account the leakage inductance of the transformer and the inductance of the filter. A simplified model is shown in Figure 2.

From this scheme the voltage equation can be written as:

$$L \frac{di_F(t)}{dt} = u_{inv}(t) - u_{syst}(t) \quad (1)$$

Where $i_F(t)$, represents the generated phase current from the converter.

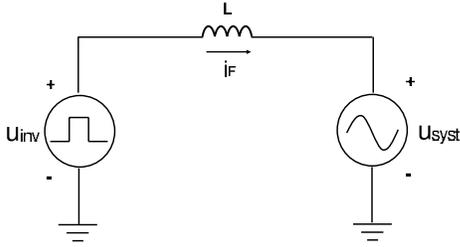


Fig. 2. Single-phase model of the shunt active power filter.

The current generated at the $(k + 1)^{th}$ sampling time instant, $i_F(k + 1)$, can be obtained in the discrete form as:

$$i_F(k + 1) = \frac{T_{sw}}{L}[u_{inv}(k) - u_{syst}(k)] + i_F(k) \quad (2)$$

Where, T_{sw} , is the sampling time. It is considered that the generated phase current $i_F(k + 1)$ tracks the reference current signal in the next period, $i^*(k + 1)$, as can be seen in Figure 3 and (3). The reference signal is obtained subtracting the load current to the desired compensated line current.

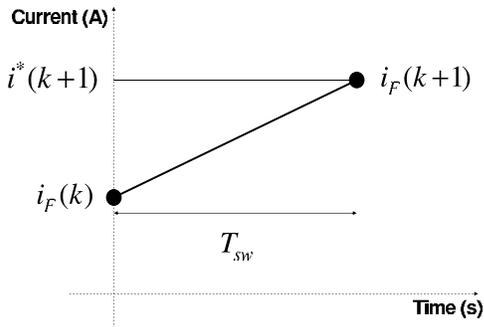


Fig. 3. Tracking of the current reference.

$$i_F(k + 1) = i^*(k + 1) \quad (3)$$

From (2) and (3), the active filter control law is obtained as:

$$u_{inv} = \frac{L}{T_{sw}}(i^* - i_F) + u_{syst} \quad (4)$$

Each phase of the converter is connected to the positive or negative side of the dc bus (V_{dc}). The converter can be conveniently modelled in Matlab introducing switching states, and supposing that the converter switches instantaneously.

A. Delta Modulation (DM)

The Delta Modulation method is a variation of the traditional hysteresis current regulator [5]. This method consists in applying

a constant voltage during the switching period. The aim of the control is to obtain the switching signals from the comparison between the current error and a fixed tolerance band (normally this band is close to 0). If the current error is positive, the inverter voltage output must be positive and if the error is negative, the inverter voltage output must be negative. During a regular interval T_{sw} synchronized with the switching frequency, the voltage is held constant. Figure 4 shows the basic principle of this control strategy.

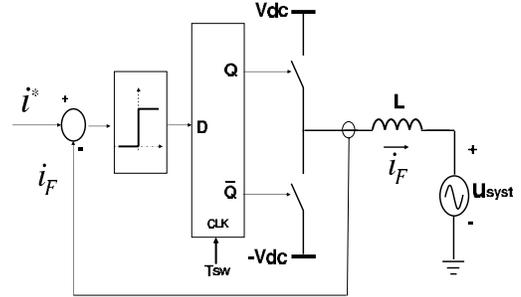


Fig. 4. Delta modulation-basic scheme.

This scheme can be viewed as a high gain proportional controller. The hysteresis band in the traditional controller adds a small phase lag in the tracking process whereas in the DM method this lag can be minimized. The major advantages of this controller are its simple implementation and its dynamic performance.

B. PI regulator with triangular carrier (PI)

This control performs a sine-triangle PWM voltage modulation of the power converter using the current error filtered by a proportional-integral (PI) regulator. In each phase there is a linear PI regulator which compares the current reference and the current filter, and consequently generates the command voltage. The regulation principle is shown in Figure 5.

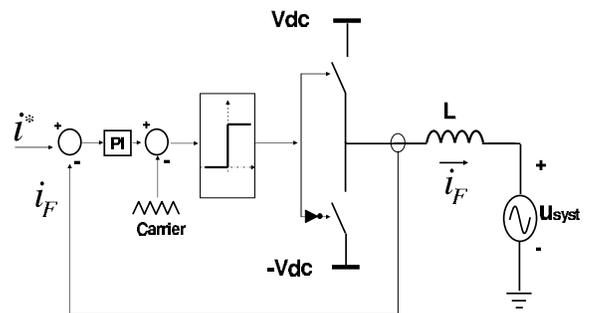


Fig. 5. Current regulator with PI controller.

In this case, the time instants at which each switching action is to be performed are evaluated analytically. In this carrier-wave based method (Figure 6), where the switching frequency is equal to the sampling frequency, the command voltage is compared with a triangular wave. If the command voltage is higher than the triangular wave, then upper switching devices are turned on and the lower switching devices are turned off.

In this control strategy the number of switching during each sampling interval can be higher than in the delta modulation control.

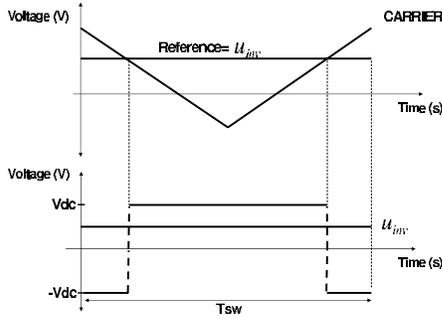


Fig. 6. Waveforms of voltage converter in PI control.

Due to the uniform sampling, the reference voltage, u_{inv} is constant during the sampling interval, T_{sw} . The proportional (K_P) and integral (K_I) parameters of the PI regulator were chosen considering the mathematical model give in Equation (4).

$$u_{inv} = K_P(i_F^* - i_F) + \frac{K_I}{s}(i_F^* - i_F) \quad (5)$$

The simulation results have shown that the dynamical response is improved adjusting the gain of the proportional part, K_P , greater than $2L/T_{sw}$ and the gain of the integrator, K_I , equals to the frequency of the triangular wave form (switching frequency). A PI-controller is commonly used to provide a high DC gain, which eliminates steady-state errors. However, as the bandwidth remains unchanged, this implies significant errors and delays in the tracking of the high order harmonics components of the current reference. For this reason, in active filtering applications, these errors usually result in a not completely satisfactory compensation quality.

C. Control method based on dead beat current control

In the conventional digital dead-beat control schemes, the regulator calculates the phase voltage to make the phase current reach its reference by the end of the following modulation period.

In this paper, a modified Method Based on Dead-Beat controller is used (MBDB). The purpose of this method is to compute directly the time period when a switching device is turned on in order to make the phase current reach its reference by the end of the following modulation period.

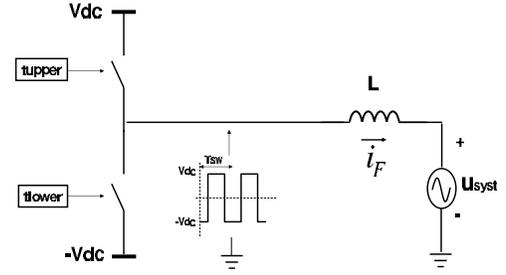


Fig. 7. Current regulator based on dead beat control.

The duration of the switching action is calculated considering the average value of the inverter voltage during a sampling interval T_{sw} . This voltage is based on (4).

$$\bar{u}_{inv} = \frac{L}{T_{sw}}(i^* - i_F) + u_{syst} \quad (6)$$

Where \bar{u}_{inv} , is the average value of inverter output voltage in a sampling interval T_{sw} and according to the waveform of Figure 8, it can be considered as:

$$\bar{u}_{inv}(k) = \frac{V_{dc}}{T_{sw}}(2t_{upper} - T_{sw}) \quad (7)$$

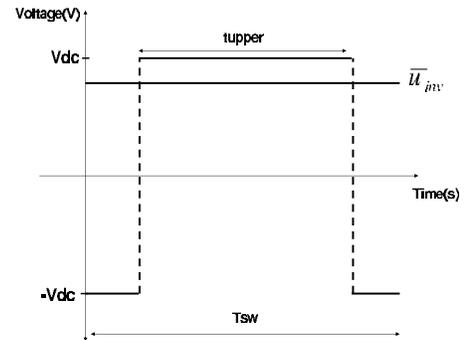


Fig. 8. Waveforms of voltage converter.

Where t_{upper} , represents the time period a switching device is turned on during a sampling interval.

The duration, t_{upper} , can be obtained from (6) and (7):

$$t_{upper} = \frac{L}{2V_{dc}}[i^* - i_F] + \frac{T_{sw}}{2} + \frac{u_{syst}T_{sw}}{2V_{dc}} \quad (8)$$

A more convenient way of expressing the duration, t_{upper} , is to minimize the average error between the reference current, i^* , and the current filter i_F , in a sampling period T_{sw} [4].

Consequently, in this work, the duration, t_{upper} is obtained by (9).

$$t_{upper} = \frac{L}{V_{dc}}[i^* - i_F] + \frac{T_{sw}}{2} + \frac{u_{syst}T_{sw}}{2V_{dc}} \quad (9)$$

And the filter current waveform is shown in Figure 9.

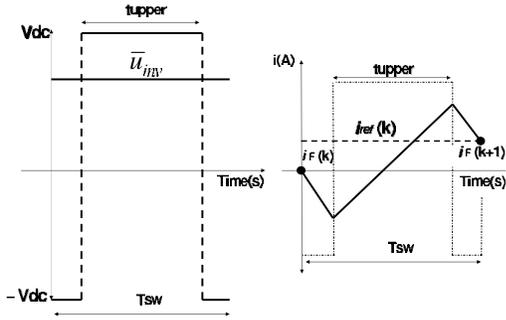


Fig. 9. Tracking of the current reference.

The main problem with a deadbeat controller is that it is very sensitive to system parameters, although is the method that ensures the best dynamic response. On the other hand, the delay due to the calculations is one of the more important limitations for applying it in active filtering applications. A solution to this problem, it is to execute the control routines twice in a modulation period, in this way the turn-on and turn-off times of the power converter switches are computed in two successive control periods.

D. Current reference

In this section, the performance of the three current control schemes is compared with different waveform current references: a) Sinusoidal Current waveform, b) Quasi-square current waveform that is a typical current waveform in industrial applications with brushless DC motors and c) Disturbed current waveform with a high level of harmonic component. In Figure 10, these waveform for a 50 Hz fundamental frequency are shown.

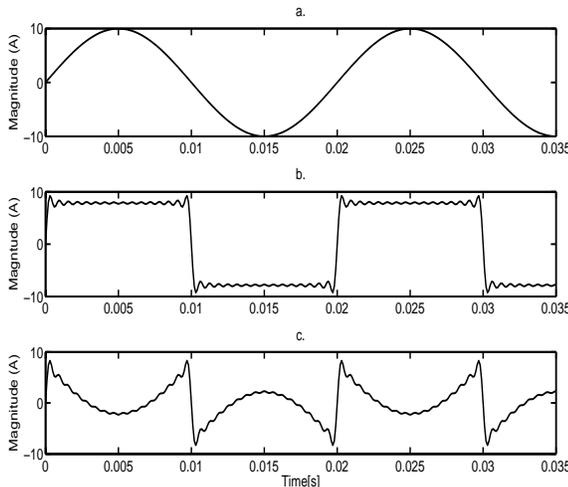


Fig. 10. Current reference. a. Sinusoidal reference, b. Square reference, c. Harmonics of signal b.

E. Criteria for the comparison of the control methods

To measure the capability to follow the current reference and evaluate which of the studied methods has a better performance three criteria are defined. Equation (10) shows the quasi-instantaneous mean error between the current active filter and the reference current. The resulting criteria gives an idea of the average error in a switching period T_{sw} , (Figures 6, 8 and 9). Being this lapse of time much shorter than the period of the main wave, the error can be considered instantaneous. Notice that the difference is not done in absolute value and the sign in every sample is conserved in the integral.

$$\Delta i(t) = \frac{1}{T_{sw}} \int_0^{T_{sw}} [i(t) - i^*(t)] dt \quad (10)$$

The root mean square error in a period of the fundamental frequency evaluates the ripple in the waveform created by the active filter. The units of this criteria are amperes as before. However, the value is not instantaneous but averaged in a long period of time. This attenuates the effect of peaks in the reference current that would give a large instantaneous error. The equation is shown in (11).

$$\delta i(t) = \sqrt{\frac{1}{T} \int_0^T [i(t) - i^*(t)]^2 dt} \quad (11)$$

Finally, to evaluate the quality of the compensated signal, the current in the source, the criteria used is the total harmonic distortion as defined in:

$$THD = 100 \sqrt{\sum_{h \neq 1} \left(\frac{I_h}{I_1} \right)^2} \quad (12)$$

The THD measures the harmonic content of a signal referred to the first harmonic. The lowest its value is the better the waveform is. The criteria defined in (10) and (11) evaluate the ability of the algorithm to follow the reference; whereas (12) measures the overall quality of the signal.

III. ACTIVE FILTER SIMULATION

The simulations are based on the active filter presented in Figure 1. The DC voltage was set to $U_{dc} = 350$ V, the phase to neutral source voltage $U_{an} = 230$ V and the inductance, $L = 20$ mH.

In the study, the switching frequency was 10 kHz. However, the PI and MBDB methods involve two commutations by switching period so the switching frequency for the Delta Modulation method was established as 20 kHz.

A. Pure sinusoidal reference (signal a)

In Figures 11, 12 and 13, the methods under study are compared in terms of the quasi-instantaneous mean error and root mean square error, using a sinusoidal waveform reference. On the left figures are plotted the reference and the filter current. The former

is the sawtooth-like sinusoid and the latter is the smooth one. On the right figures is plotted the instantaneous error calculated as the difference between the previous currents.

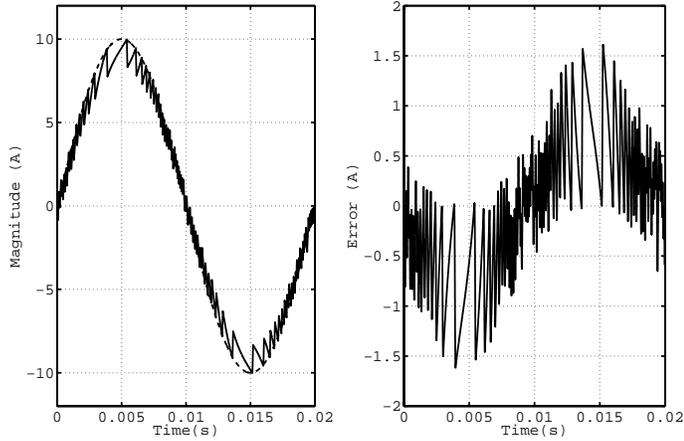


Fig. 11. DM method. Left: Filter current and current reference, Right: Instantaneous error.

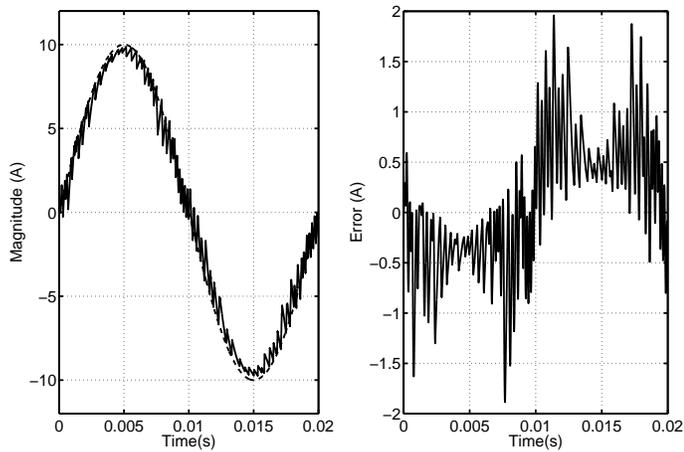


Fig. 12. PI method. Left: Filter current and current reference, Right: Instantaneous error.

It is important to notice the scale of the error plots. The last method has clearly the lowest instantaneous error. Table I shows the figures of merit for this type of waveform and for every method. The root medium square error is calculated in a period of 50 Hz. Again, the results shown in Table I confirm that the MBDB method has the best performance.

TABLE I

	DM	PI	MBDB
$\Delta i(t)$	1.610	1.959	0.206
$\delta i(t)$	0.692	0.644	0.129

B. Quasi-square current waveform reference (signalb)

As it was done in subsection III-A, the Figures 14, 15 and 16 are the simulation of the methods under study. The current

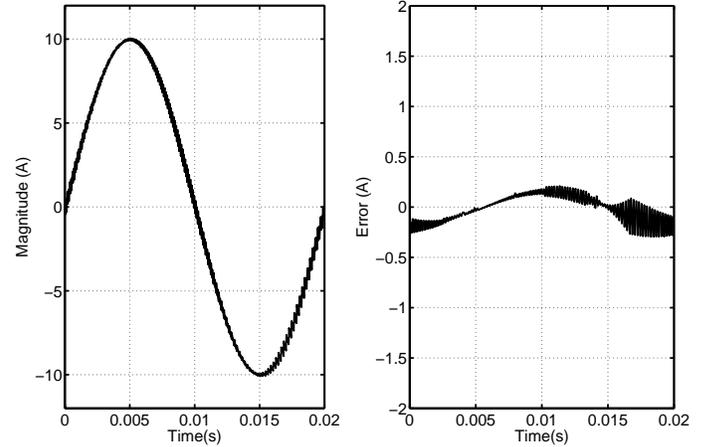


Fig. 13. MBDB method. Left: Filter current and current reference, Right: Instantaneous error.

reference is a square waveform with finite upward and downward slope. The criteria are collected in Table II. Though the errors

TABLE II

	DM	PI	MBDB
$\Delta i(t)$	9.643	10.685	10.266
$\delta i(t)$	1.584	1.834	1.626

in these cases are notably larger than with the pure sinusoid in subsection III-A, the control strategy was not changed. As it might be expected, the tracking errors soar in the sections where the current derivative is larger. The filter algorithm is not longer able to properly follow the reference. The ability to follow infinite slopes is more a matter of the dimension of the filter than the dimension of the algorithm itself.

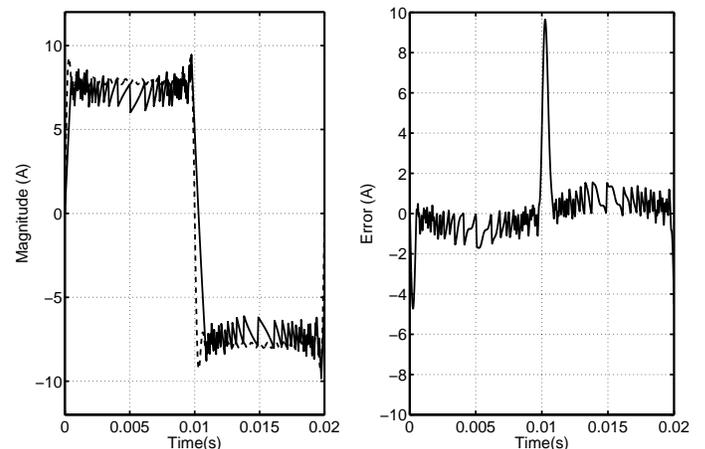


Fig. 14. DM method. Left: Filter current and current reference, Right: Instantaneous error.

C. Simulation with the signal c

The signal in this simulation is a square waveform without the main harmonic. The results are very similar to the ones obtained

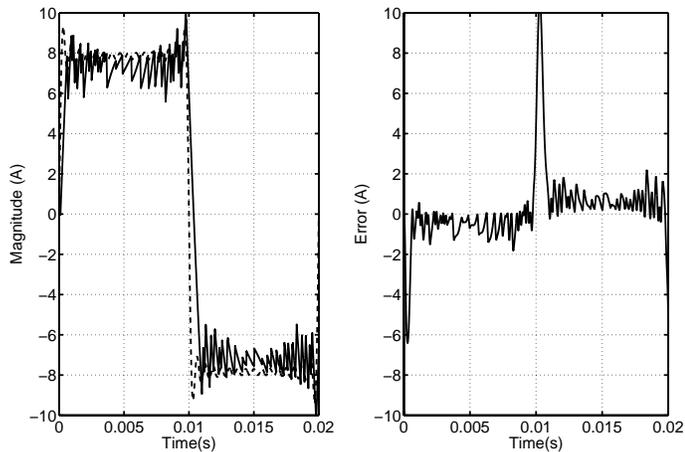


Fig. 15. PI method. Left: Filter current and current reference, Right: Instantaneous error.

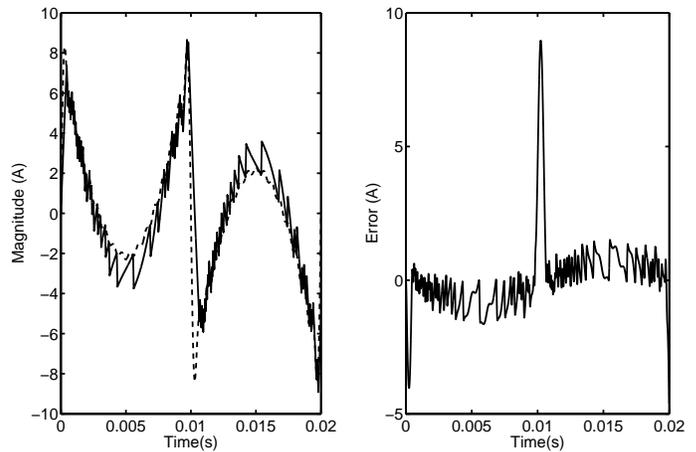


Fig. 17. DM method. Left: Filter current and current reference, Right: Instantaneous error.

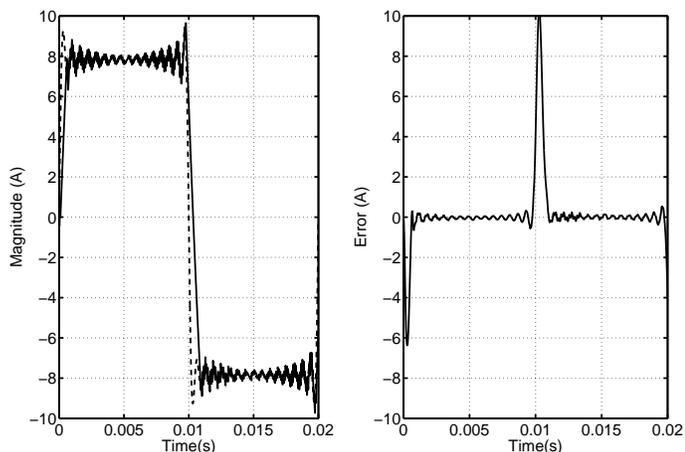


Fig. 16. MBDB method. Left: Filter current and current reference, Right: Instantaneous error.

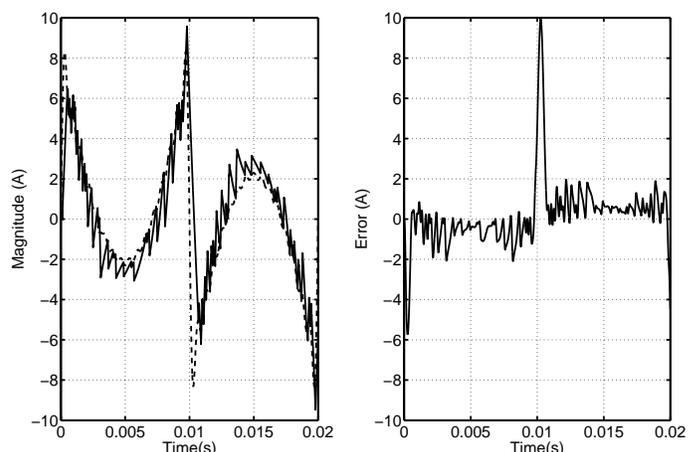


Fig. 18. PI method. Left: Filter current and current reference, Right: Instantaneous error.

in the last section. The performance of the strategies is really good being the MBDB method the most outstanding.

Table III shows the results of the criteria of merit for this waveform. It can be concluded that the three strategies work adequately for a good performance of the active filter.

TABLE III

	DM	PI	MBDB
$\Delta i(t)$	8.962	9.926	8.744
$\delta i(t)$	1.461	1.674	1.330

IV. PRACTICAL APPLICATION

A simple model for an adjustable speed drive, ASD, is employed as the main source of harmonic distortion. In order to test the active filter performance at different situations. The Matlab/Simulink software is used to model both the non linear load and the active filters in the time domain. This simulated model has been validated with real measurements from a laboratory

experiment with a real motor. The reference current is based on the Fryze theory, the DC control was implemented with a PI, and the current control was implemented with the MBDB control. Finally, a simple model for an adjustable speed drive, ASD, is employed as the main source of harmonic distortion.

The waveform to be corrected is the current measured at the input terminals of the load. It is plotted in Figure 20. The results for the control strategy are shown in Figures 21 and 22. It can be clearly seen that the signal is corrected and a sinusoidal wave substitutes the original waveform when the filter is connected.

The figure of merit appropriate for this study is the THD for both signals. Table IV shows the values for the current before and after the compensation. It is worth noticing the outstanding performance of the filter reducing the THD more than fifteen times.

TABLE IV

Without compensation	With compensation
125 %	7.89 %

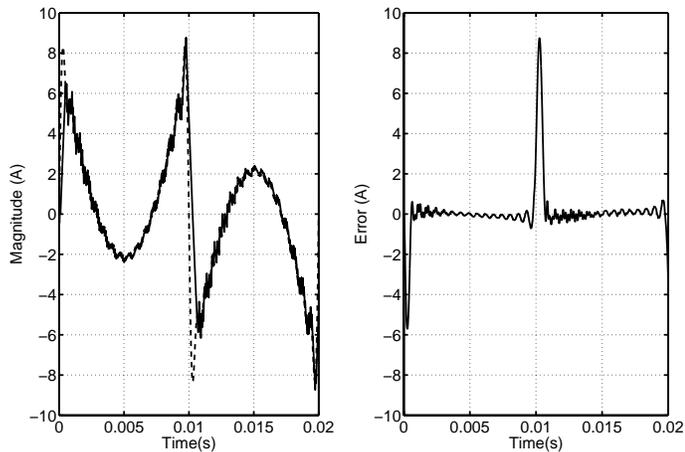


Fig. 19. MBDB method. Left: Filter current and current reference, Right: Instantaneous error.

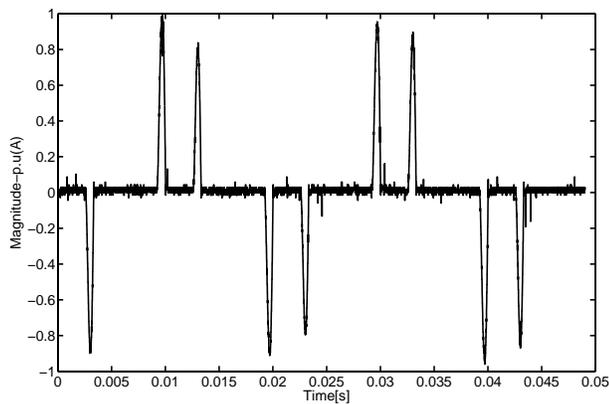


Fig. 20. Current measured at the input terminals of the non-linear load.

V. CONCLUSIONS

In this paper an active power filter implemented with three different current control methods has been presented and analyzed. The control strategies have been compared and the results obtained show that the best performance is obtained with the method based on a dead beat controller, it has to be noted that the systems parameters are known accurately. For the sake of simplicity and easy implementation, the method based on Delta Modulation can be utilized. All the methods have difficulties to track large slope currents. However, this is a problem of the active filter and it is due to its incapacity to generate an infinite slope current (di/dt). A practical application considering an adjustable speed drive has been analyzed correcting the current drawn by the non-linear load. The results improve the THD from an extremely high 125 % to a much more convenient 7.89 %.

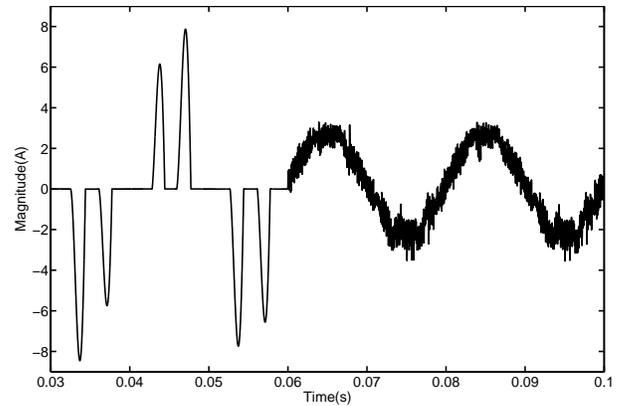


Fig. 21. The results of the control strategy.

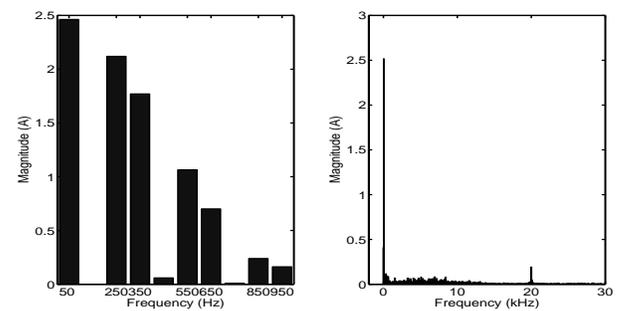


Fig. 22. Spectrum. Left: Without compensation, Right: With compensation.

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