Evaluation of Stationary Frame and Fixed Switching Frequency Digital Current Control Techniques for Power Active Filters

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Keywords

Converter control, active filter, harmonics

Abstract

In this paper two stationary frame digital current control techniques, the RST and the Multi-Resonant controller, are analysed and experimentally tested in an active filter application. The RST controller has been tuned in order to obtain a deadbeat response. The method used to tune the Multi-Resonant controller is based on a frequency response approach that guarantees the stability and robustness of the system. It is well-known that the performance of deadbeat controllers is constrained to the accuracy of the plant model as well as the accuracy of the reference and disturbance predictions. The accuracy of the Multi-Resonant controller is guaranteed as long as the system is stable and the harmonics of the reference and the disturbance coincide with the resonance frequencies of the controller. Theoretically the main advantages of the deadbeat controller are its simplicity and its dynamics. However, in a complex application such as the active filtering the intrinsic delay of the controller is unacceptable and therefore it is necessary to use reference (and eventually disturbance) prediction techniques. The use of these techniques can have a non-negligible effect on the characteristics of the system and can be detrimental for both the dynamics and the simplicity of the system. In this paper two different prediction techniques have been implemented: periodicity and resonant. It is shown that the steady-state performances in both cases are satisfactory and similar to those obtained with the Multi-Resonant controller. Nevertheless, the first of the prediction techniques deteriorates significantly the dynamic performance of the system while the second one increases considerably its complexity, showing that the Multi-Resonant controller is better adapted for this kind of applications than the studied deadbeat controller.

1 Introduction

Active filtering is one of the most challenging applications for digital current controls as it is necessary to handle not only with fundamental currents but also with harmonics. Various controllers have been proposed in the literature both working in stationary and synchronous frame and operating in fixed and variable switching frequency.

In this paper two different digital stationary frame current control techniques are analysed: the RST and the Multi-Resonant controller. The RST controller has been tuned in order to obtain a deadbeat response (i.e. it makes the system response as a double delay) [1]. The Multiple-Resonant controller is based on multiple resonant regulators [2] [3], each of them tuned to the pulsation of a particular harmonic. As these integrators respond to sinusoidal errors, the controller is able to eliminate not only the amplitude error of the current but also the phase error [4].

In a complex application such as the active filtering the intrinsic delay of the deadbeat controller (RST) is unacceptable and therefore it is necessary to use reference (and eventually disturbance) prediction techniques. In this paper two different families of prediction techniques are analysed and tested: *sliding window-based* and *regulator-based* prediction techniques.

The main characteristic of *sliding window-based techniques* is that they use one or various stocked periods in order to predict the evolution of a particular signal. The difference between them lies in the treatment of the stocked information. In [5] a predictor with learning abilities is proposed. This predictor combines two modules: one for periodic slowly variating signals, which by observing several past periods learns the characteristics of the signal by the minimum mean square error method, and the other one for high frequency random fluctuating signals, approximating the instantaneous change of high-frequency fluctuating signals by a n-th degree series function. A relatively accurate prediction of the input signal is achieved both in transient and steady-state conditions. Nevertheless, the complexity of the technique is considerable. Other authors [6] propose simpler techniques, based on the periodicity of the input signal, where the output signal is assumed to be equal to the input signal half a line-period plus two samples back. This is a much simpler technique (no need to treat the stocked information) that presents good performances in steady-state, but a quite poor response in transient conditions.

Concerning *regulator-based* prediction techniques, they operate on the base of the minimisation of the error between the delayed prediction and the present input signal. In [7] a resonant regulator based predictor is proposed. This technique permits to improve the transient response of the prediction but it only works if the frequency spectrum of the input signal is well known.

The main goal of this paper is to compare the two mentioned digital current control techniques for shunt active filter applications. The theoretical advantages of the deadbeat controller, its simplicity and its dynamics, are questioned by the necessity of prediction techniques. The comparison between controllers has been carried out theoretically and experimentally, considering various criteria, such as their performances in terms of transient response, steady state error, robustness and computational load.

2 Physical system representation

Fig. 1 presents the single-phase equivalent scheme of a grid-connected inverter, the core of a shunt active filter.

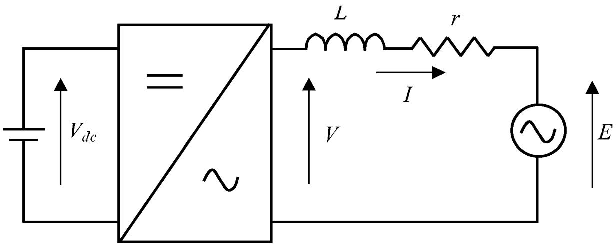

Fig. 1: Single-phase representation of a grid-connected active filter.

If the inverter is considered to be an ideal sinusoidal voltage source, the transfer function of the plant is given by the transfer function of an inductive filter (depicted in equation (1) in continuous and discrete time). The first term of this equation represents the transfer function between the output current (*I*) and the inverter output voltage (*V*) while the second term corresponds to the transfer function between the output current (*I*) and the disturbance (*E,* grid voltage).

$$I(s)=\frac{1/L}{s+r/L}V(s)-\frac{1/L}{s+r/L}E(s) \quad \Rightarrow \quad I(z)=\frac{a}{z-b}V(z)-\frac{c(z+1)}{z-b}E(z) \tag{1}$$

where a, b and c depend on the values of the filter (r and L).

3 Multi-Resonant Controller

3.1 Presentation of the structure and the tuning method

The structure of a resonant regulator is similar to the structure of a PI, with a proportional gain k_p and an integral gain k_i. The integral term contains complex conjugated poles in order to achieve an infinite gain at the chosen frequencies. As a result, it guarantees a zero static error at these frequencies. The continuous and discrete transfer functions of a resonant controller (considering a cosine implementation) are:

$$C(s)=k_p+\frac{2k_i s}{s^2+\omega_0^2} \qquad C(z)=k_p+\frac{2k_iT_s\left[z^2-\cos(\omega_0T_s)z\right]}{z^2-2\cos(\omega_0T_s)z+1} \tag{2}$$

In the case of an active filter application, as much resonant controllers as harmonics to be controlled are needed (regardless of their sequence). Fig. 2 (left hand) shows the asymptotic frequency response of a Multi-Resonant controller (harmonics 5, 7, 11 and 13) and (right hand) the parallel structure chosen in this paper.

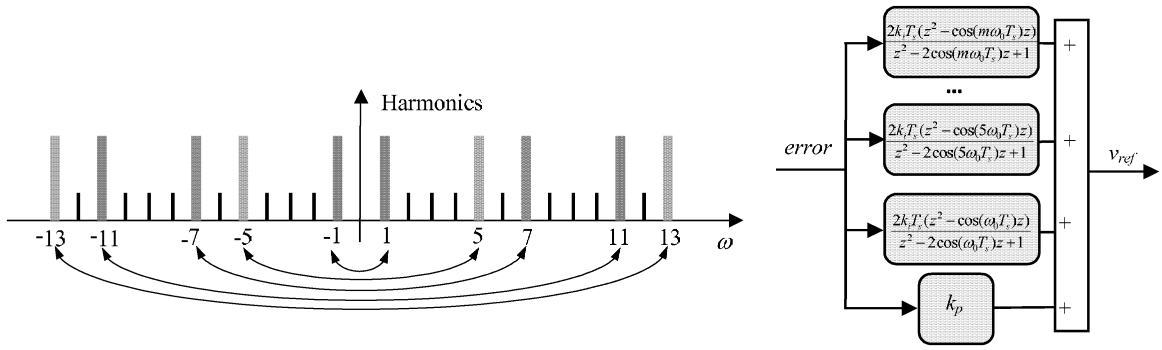

Fig. 2: Frequency response (left) and chosen structure (right) of the Multi-Resonant controller.

Concerning the tuning method, a frequency response approach has been used. The objective is to guarantee a sufficient phase margin (PM) for the system, taking into consideration the effects of the digital implementation related delays. In this method the proportional gain (k_p) is calculated from a chosen open-loop bandwidth value (BW_{OL}):

$$k_p=L\sqrt{BW_{OL}^{\;2}-\left(\frac{r}{L}\right)^2} \tag{3}$$

The bandwidth must be carefully chosen. On the one hand it must be higher than the highest controlled harmonic (h_m) to guarantee a sufficient phase margin and on the other hand small enough to avoid an excessive degradation of the phase margin by the digital implementation related delay. Regarding the calculation of resonant parameters (k_{in}), the objective is to minimize their influence on the phase margin of the system. For instance the phase addition ($\Delta\Phi$) of resonant terms at BW_{OL} can be limited to 5° .

3.2 Implementation

The Multi-Resonant controller has been designed for an active filter application dealing with the fundamental and harmonics 5, 7, 11 and 13 . The system and sampling parameters are shown in Table I and the controller parameters are presented in Table II.

Table I: Physical Sampling Parameters

Symbol	Magnitude	Value
r	Filter resistance	0.028 Ω
L	Filter inductance	3 mH
T_S	Sampling period	100 μs

Table II: Control Parameters

Symbol	Magnitude	Value
h_m	Highest harmonic	4085 rad/s
BW_{OL}	Bandwidth	5000 rad/s
PM	Phase Margin	42°
$\Delta\Phi$	Phase addition	5°
k_p	Proportional Parameter	15
k_i	Resonant Parameter	400

With these parameters the characteristics of the system have been validated by means of the open-loop and closed-loop frequency responses of the global system (controller + calculation delay + plant). As it can be seen in Fig. 3 (left) the open-loop bandwidth of the system is approximately 5000 rad/s and the phase margin is relatively high (42°). Concerning the closed-loop response (Fig. 3 right hand), even if the gain and the phase at the selected harmonic frequencies are zero, there is a resonance that appears at the range of 4000-10000 rad/s which is directly related to the chosen proportional parameter value [8].

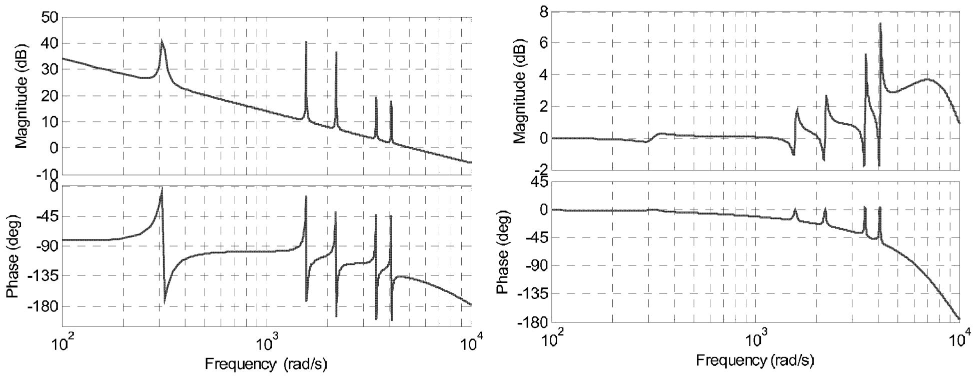

Fig. 3: Open-loop (left) and closed-loop (right) frequency responses (Multi-Resonant controller).

4 RST deadbeat controller

4.1 Presentation of the structure and the tuning method

4.1.1 Tuning of the controller

The control method consists in adding to the system three control polynomials (R, S and T) in order to be able to place the closed loop poles in the desired locations and, in this way, obtain the desired behaviour of the system. Fig. 4 shows the block diagram of the system composed of the RST controller, the calculation delay and the plant.

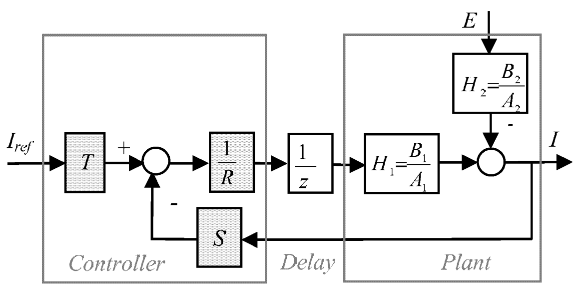

Fig. 4: Block diagram of the RST controller, the calculation delay and the plant.

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where H_1 is the transfer function between the output current related and the reference and H_2 is the transfer function between the output current and the disturbance.

The closed-loop discrete transfer function of this system is:

$$I(z)=\underbrace{\left(\frac{B_1 T}{zA_1R+B_1S}\right)}_{CLref}I_{ref}(z)+\underbrace{\left(\frac{B_2zA_1R}{A_2(zA_1R+B_1S)}\right)}_{CLdis}E(z) \qquad (4)$$

As a second-order active filter model is considered (the calculation delay + the L filter), two control parameters are necessary in order to tune the closed-loop system:

$$\begin{aligned} S &= s_0 z + s_1 \\ R &= z + r_1 \end{aligned} \qquad (5)$$

Hence, the denominator of CL_{ref} will be:

$$zA_1R+B_1S = z^3+z^2(r_1-b)+z(-br_1+as_0)+as_1 \qquad (6)$$

To obtain a deadbeat response all the coefficients of equation (6) must be zero. Thus:

$$s_0=\frac{b^2}{a},\quad s_1=0,\quad r_1=b_1 \qquad (7)$$

The closed-loop transfer function becomes:

$$CL_{ref}=T\frac{B_1}{z^3} \qquad (8)$$

A double delay response can be achieved if the polynomial T is:

$$T=\frac{z}{B_1} \qquad (9)$$

4.1.2 Delay compensation

With the analysed RST dead-beat response controller a perfect delayed response is obtained. In applications in which high frequency components have to be controlled (as it is the case of active filtering) this delay is unacceptable. Since the delay is well known (two sampling periods) it can be compensated by means of a prediction on the reference. In this work two prediction techniques have been analysed: the resonant prediction and the periodicity-based prediction.

a) Resonant prediction

The resonant prediction is based on resonant terms. A prediction loop, in which the output is delayed by the desired prediction-time, can be built in order to compensate the delay (see Fig. 5). It must be remarked that as much resonant terms as harmonic components evolutions to be predicted are necessary.

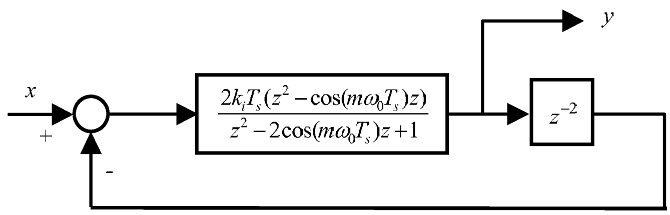

Fig. 5: Prediction of a signal by means of a resonant prediction.

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b) Periodicity-based prediction

In steady state, supposing that the reference signal is periodic, a prediction of the reference can be made from the values stored in the memory (see Fig. 6). In this figure, T_s is the sampling period, T is the reference period and n is an integer value which goes from one to $T/2T_s$. It must be remarked that this compensation method actually consists in decaling the reference almost half a period. Consequently, in transient state the tracking error will be significant.

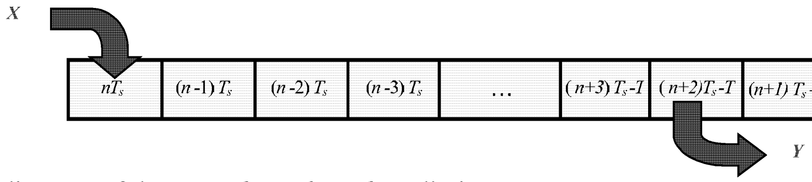

Fig. 6: Block diagram of the *periodicity-based* prediction.

4.1.3 Disturbance rejection

The calculated RST controller is not able to correct the disturbance effect. In order to minimise this effect a compensation term has been added (C) to the controller (see equation 10). The expression not being causal, a double delay has been added (C_c). This delay is compensated using a prediction technique, as it is shown in Fig. 7.

$$C = \frac{cz^2 + cz}{a} \quad \rightarrow C_C = \frac{cz^2 + cz}{az^2} \tag{10}$$

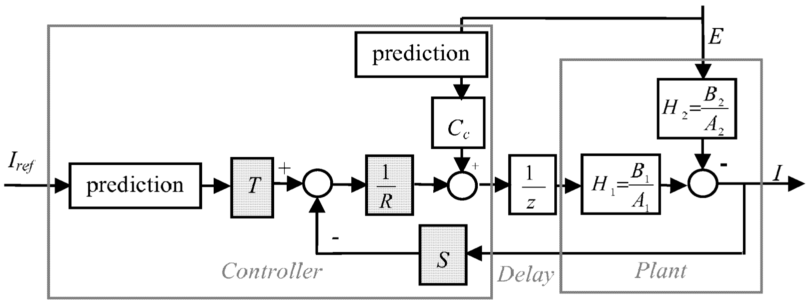

Fig. 7: Block diagram of the RST controller (with predictions and disturbance rejection) and the plant.

4.2 Implementation

The presented control structure and tuning approach have been implemented in an active filter application. The objective is to design a control structure that is able to handle with harmonics 5, 7, 11 and 13 (in addition to the fundamental). The system and sampling parameters are shown in Table I and the controller parameters deduced from equations (4) to (10) are presented in Table III.

Table III: Control Parameters

Control polynomials	Value
R	$z + 0.999$
S	$29.95\,z$
T	$\frac{z}{0.03332}$
C	$\frac{0.01666\,z^2 + 0.01666\,z}{0.03332\,z^2}$

Fig. 8 shows the open-loop (left) and closed-loop (right) frequency responses of the whole system (controller + calculation delay + plant). As it can be seen the open-loop bandwidth of the system is

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approximately 5000 rad/s and the phase margin is relatively high (60°). The closed-loop frequency response shows the ideal case, "constant" filtering capabilities for all frequencies (considering a perfect knowledge of the parameters of the system).

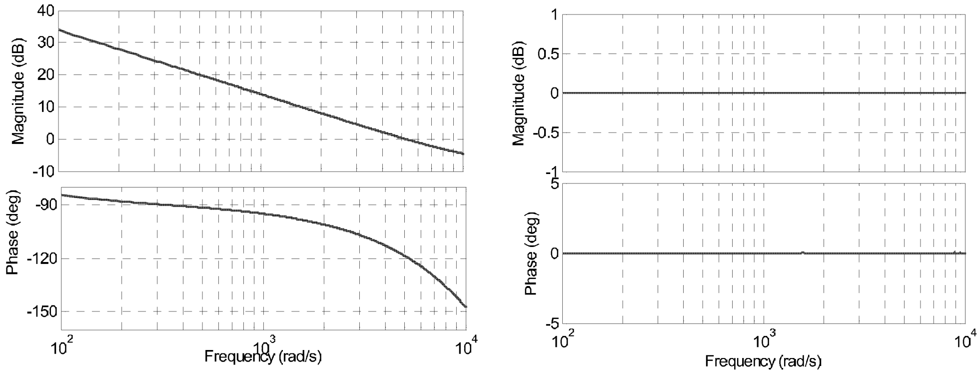

Fig. 8: Open-loop and closed-loop frequency responses of the system with the RST controller.

5 Experimental and theoretical comparison

The comparison between these structures has been carried out based on various theoretical aspects, such as the computational load and the robustness, and some experimental aspects, such as transient and steady-state performances of the system.

5.1 Theoretical performances

5.1.1 Computational load

If the prediction is not taken into consideration (Tables IV and V), the RST controller requires much less addition/subtraction and product/division operations than the Multi-Resonant controller.

Table IV: Operations required by the Multi-Resonant controller (3 wires topology)

Harmonics	+/-	x/%	m
1, 5, 7	25	20	16
1, 5, 7, 11	33	26	20
1, 5, 7, 11, 13	41	32	24

Table V: Operations required by the RST controller (3 wires topology)

Harmonics	+/-	x/%	m
RST controller	4	6	2
Disturbance comp.	5	2	2
Total	9	8	4

Nevertheless, this is not a realistic comparison because it is necessary to take into account the computational load and the memory allocation required by the prediction technique of the reference and the disturbance. Depending on the technique that it is used the difference can be considerable. Table VI shows the amount of operations required by the resonant prediction of a balanced 3 phase signal.

Table VI: Operations required by the Multi-Resonant prediction (3 wires topology)

Harmonics	+/-	x/%	m
1, 5, 7	29	18	24
1, 5, 7, 11	39	24	32
1, 5, 7, 11, 13	49	30	40

The requirements of the periodicity based technique depend on the size of the sliding window that is used. For example if the signal is stored each 100µs and the fundamental period is 20ms, 200 memory registers will be needed for each predicted 3 phase balanced signal. In addition 198 memory shifts will be carried out at each sampling period.

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5.1.2 Robustness analysis

In the RST deadbeat controller it is necessary to know quite exactly the values of the system parameters because not only the stability but also the response accuracy depends enormously on the precision of the parameters used in the controller [8]. This fact is verified in Fig. 9 where the effect of a 20% error of the inductance value is analysed.

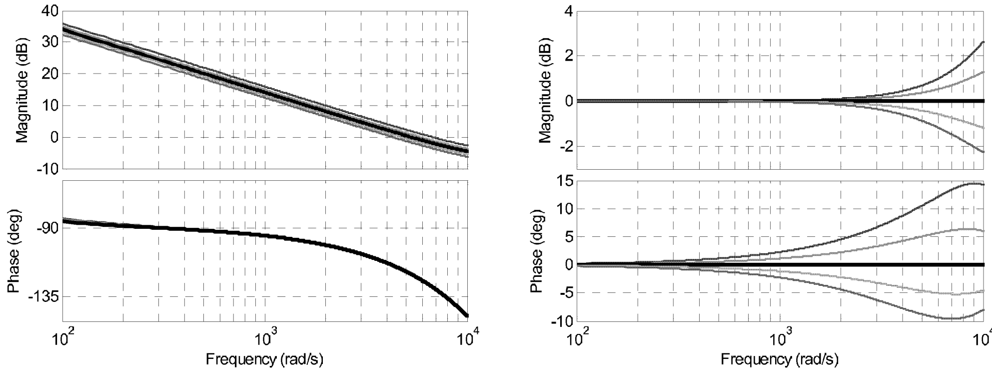

Fig. 9: Open-loop (left) and closed-loop (right) frequency responses with a L identification error of ± 20% (dark curve without error) with the RST controller.

In contrast, the Multi-Resonant controller is quiet robust. A 20% error between the real value of L and the one used to tune the controller does not affect the accuracy of the open-loop and closed-loop responses at the desired frequencies. Nevertheless, this error can provoke the amplification of the resonance phenomenon at high frequencies as it can be seen in Fig. 10 (right).

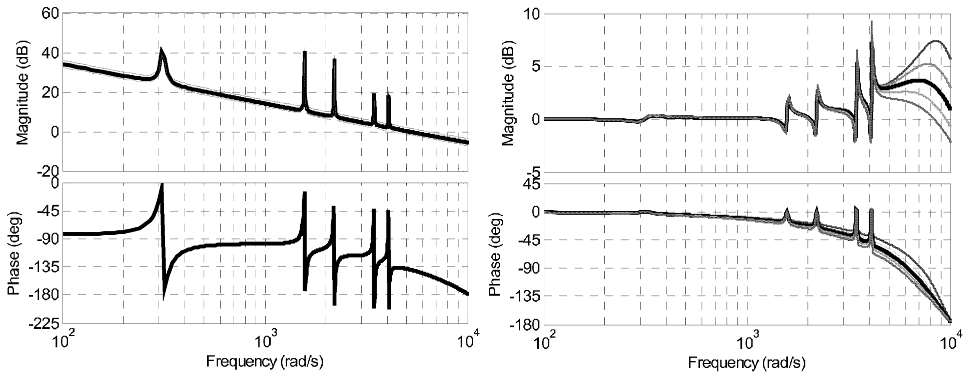

Fig. 10: Open-loop (left) and closed-loop (right) frequency responses with a L identification error of ±20% (dark curve without error) with the Multi-Resonant controller.

5.2 Experimental performances

Presented controllers have been implemented and experimentally tested using the three-phase grid-connected system test bench of the Electrotechnical Laboratory of Grenoble, LEG (France). The test bench is based on the DS 1005 PPC Controller Board, which permits the automatic implementation of control algorithms directly from Simulink. The conventional two-level, three-leg inverter (rated in 10kVA) has been used in a 3 wires topology. The parameters of this test-bench are presented in Table VII. The current control capabilities of the proposed controllers and prediction techniques have been tested both in an arbitrary current generation application (see Table VIII) and in an active filter application.

Table VII: Implementation parameters

Symbol	Magnitude	Value
f_s	Switching frequency	10 kHz
V_{dc}	DC BUS Voltage	400 V
V	Grid Voltage	180 V

Table VIII: Arbitrary current reference

Symbol	Magnitude	Amplitude
h_1	Fundamental	8 A
h_5	5th harmonic	2 A
h_7	7th harmonic	2 A
h_{11}	11th harmonic	1 A
h_{13}	13th harmonic	1 A

5.2.1 Arbitrary current generation

The objective of these tests is to analyse the transient response of each controller and prediction technique (the fundamental current reference is reduced from 8A to 4A). Fig. 11 shows the transient response of the Multi-Resonant controller. As it can be seen the transient response is very good and the tracking error is negligible.

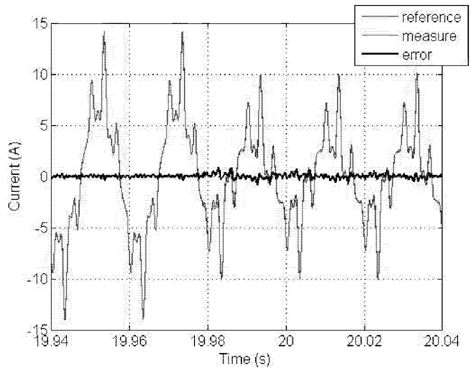

Fig. 11: Transient response of the Multi Resonant controller.

The results obtained with the RST deadbeat controller are depicted in Fig. 12, with the resonant (left) and the periodicity (right) predictors. In order to obtain realistic results, the tuning of the controller has been carried out using the theoretical values of the grid coupling filter, without considering its real value and the grid impedance value. Thus, as the controller is not optimised for this particular application, the obtained results are worse than in the previous case. Between both deadbeat controllers, as expected, the resonant predictor presents better transient performances.

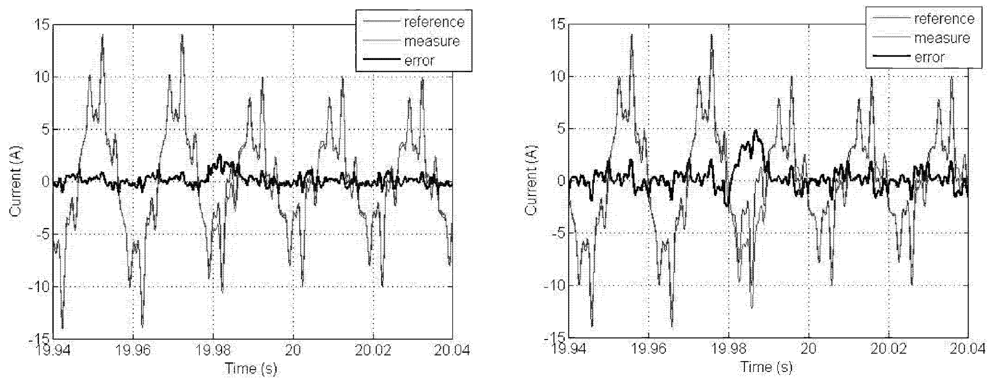

Fig. 12: Transient response of the RST controller: resonant (left) and periodicity (right) predictors.

5.2.2 Active filter application

The main objective in this case is to test the steady state performances of the system. Thus, both controllers and prediction techniques have been tested in an active filter application (a three phase diode rectifier with a capacitive filter and a resistive load has been used as non-linear load). The Instantaneous Power method has been used for the real time harmonic identification.

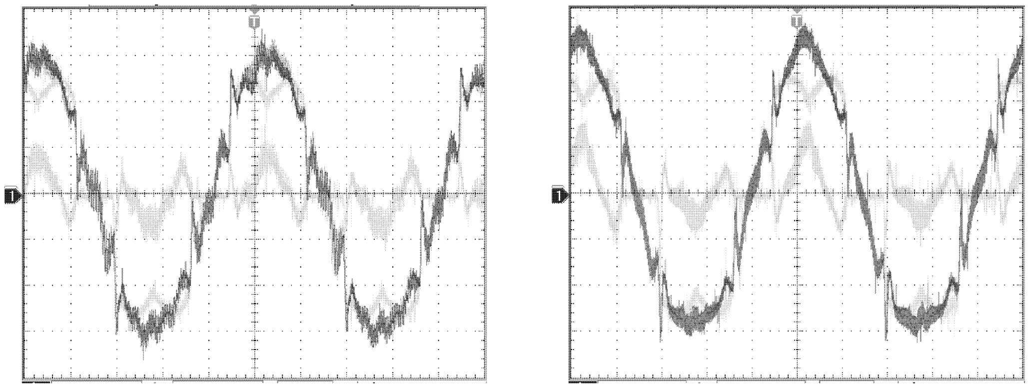

Fig. 13: Grid, load and injected currents with the RST (left) and the Multi-Resonant (right) controllers.

Fig. 13 shows the obtained grid current compared to the rectifier load current and the current injected by the active filter for both controllers (in the case of the RST controller a resonant prediction technique is used for the reference and the disturbance). In both cases the grid current is almost sinusoidal, confirming the good steady-state conditions of the two analysed controllers.

6 Conclusion

In this paper two stationary frame digital current control techniques, the RST-deadbeat and the Multi-Resonant controller, are analysed and experimentally tested in an active filter application. The theoretical advantages of the deadbeat controller, its simplicity and its dynamics, are questioned by the necessity of prediction techniques in complex applications such as the active filtering. In this paper two different prediction techniques have been implemented: periodicity and resonant, and it has been shown that the steady-state performances in both cases are satisfactory and similar to those obtained with the Multi-Resonant controller. Nevertheless the first of the prediction techniques deteriorates significantly the transient performance of the system while the second one increases considerably its complexity. The classical drawbacks of deadbeat controllers (accuracy problems) together with the weaknesses derived from the necessity of using a predictor for the reference (and eventually for the disturbance) makes the Multi-Resonant a more interesting solution for multi-frequency applications.

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