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Model Predictive Direct Power Control with Duty Cycle Control of PWM Rectifier

***Abstract**. This work proposes a model predictive direct power control (MP-DPC) to achieve direct control of active power and reactive power in PWM rectifiers. High power ripples and variable switching frequency result from conventional DPC's use of a single voltage vector during a control period. To overcome these drawbacks, a duty cycle control is applied to the MP-DPC to increase performance in terms of reducing power ripple, and achieving dynamic response. Its principal feature is the use of several voltage vectors over the course of a control period. In fact, minimizing the active power ripple during a control period determines the duration of the selected vector. Simulation results using Matlab/Simlink software showed that MP-DPC provides an improvement in system performance and a certain robustness compared to conventional DPC.*

Streszczenie.** W pracy zaproponowano model predykcyjnej bezpośredniej regulacji mocy (MP-DPC) w celu uzyskania bezpośredniej regulacji mocy czynnej i mocy biernej w prostownikach PWM. Tętnienia dużej mocy i zmienna częstotliwość przełączania wynikają z używania przez konwencjonalne DPC pojedynczego wektora napięcia w okresie kontrolnym. Aby przezwyciężyć te wady, w MP-DPC zastosowano kontrolę cyklu pracy, aby zwiększyć wydajność pod względem zmniejszenia tętnień mocy i uzyskania dynamicznej odpowiedzi. Jego główną cechą jest wykorzystanie kilku wektorów napięcia w ciągu okresu kontrolnego. W rzeczywistości minimalizacja tętnień mocy czynnej w okresie regulacji określa czas trwania wybranego wektora. Wyniki symulacji z użyciem oprogramowania Matlab/Simlink wykazały, że MP-DPC zapewnia poprawę wydajności systemu i pewną solidność w porównaniu z konwencjonalnym DPC.* (Model Predictive Direct Power Control z kontrolą cyklu pracy prostownika PWM***)

Keywords: PWM rectifier, power ripple, model predictive direct power control, duty cycle control.
Słowa kluczowe: model predykcyjny, prostownik PWM

Introduction

Recently, the increasing use of power electronics devices in electrical systems has led to enormous problems related to harmonic disturbances or distortions of electrical networks. This phenomenon affects all industrial, tertiary and domestic sectors using non-linear loads. On the one hand, these non-linear loads absorb non-sinusoidal currents which circulate through the power lines and distort the voltage of the electrical network, and on the other, consume reactive power which has the consequence of degrading the power factor.

Various solutions can be used to remedy these problems, mention may be made of passive filters, active filters and sinusoidal current absorption devices, such as PWM rectifier. Recently, the PWM rectifier has established itself as one of the best depollution solutions, which has aroused the growing int erest of researchers. Research in this area has encompassed several aspects, their topologies, the power switches used in the different structures and the control techniques of these converters. Among these most widespread and attractive structures are the PWM voltage rectifier [1-3].

Research work on PWM rectifiers has grown rapidly in recent years. These new AC/DC converters have become an attractive field of research and of great interest, for their various industrial and domestic applications and the advantages they offer, namely: the possibility of generating energy, controlling the voltage of the DC bus over a wide range, the absorption of sinusoidal currents, and the possibility of operation with a power factor close to unity. For this type of converters, many control strategies have recently been proposed in the literature with aims to achieve the same objectives, namely : a power factor close to unity and a quasi-sinusoidal waveform of the absorbed currents [4, 5].

Due to the PWM rectifiers' numerous applications, a variety of approaches have been proposed to achieve high-performance power control of the PWM rectifiers. The two most well-known among these are voltage oriented control (VOC) [6] and direct power control (DPC) [7]. DPC's simple structure provides very quick response. However, high power ripples and variable switching can be observed because of an included switching table and the current harmonics are distributed over a wide frequency range, and these are some of its drawbacks [7, 8]. To overcome these drawbacks, improved DPC have been reported in the literature [9-13]. In order to obtain fast and robust power response and to solve the problems caused by the power ripple, some authors have revised the conventional switching table by proposing new switching tables [14], and fuzzy logic selection to select the desired voltage vectors [15].

Recently, the model predictive control (MPC) has become a robust control strategy for motor drives [16, 17] and power converters [18-22]. MPC can generally be classified into two categories: FCSMPC with discrete input and conventional MPC with continuous input [23]. In comparison to the DPC, the FCSMPC predicts the future behavior of the variables over a range of time horizons by substituting an accurate system model for the heuristic switching table. To penalize the impact of different voltage vectors on the tracking error between the predicted value and the reference value, a cost function is designed. It is decided that voltage vector is optimal by minimizing the cost function. The prediction and optimization steps are repeated in the next control period, ensuring that the applied voltage vector is optimized in instantaneously [24, 25]. [26] proposed a predictive direct power control of a PWM rectifier under unbalanced grid voltages using a new definition of the instantaneous reactive power in the predefined cost function.

In this work, we will propose new DPC structure, which allows to obtain sinusoidal network currents. An improvement is introduced in the structure of the conventional DPC, by proposing a model predictive direct power control (MP-DPC) as a powerful and more precise and efficient alternative in vector selection compared to the conventional DPC, and the improved DPC. By selecting the best voltage vector by minimizing a cost function consisting of power errors and by using the duty cycle, better steady-state performance in terms of power ripples and current harmonics is achieved. The effectiveness of this strategy is validated by simulation tests.

This work is organized into four sections to better serve the objectives of our research: The two-level PWM rectifier power circuit was modeled and shown in section 2. Section 3 will be entirely dedicated to the model predictive direct power control of the PWM rectifier. An appropriate mathematical model will be established and analyzed to predict future values of active and reactive power. The minimization of the cost function consisting of power errors makes it possible to determine the optimal control vector among the set of possible vectors to be applied to the rectifier input during each switching period. Then, duty cycle control is then introduced to the MP-DPC to achieve a reduction in the power ripple and quasi-sinusoidal main currents. Simulation results and discussion are presented in section 4 followed by a final conclusion.

Modeling of the PWM rectifier

The modeling step is very important. It is a question of finding a relation between the control quantities and the electrical quantities of the alternating and continuous part of the rectifier. In this study, we have also opted for a variable topology modeling method, which consists in considering semiconductors as perfect switches with instantaneous switching, having two possible states: closed and open [14].

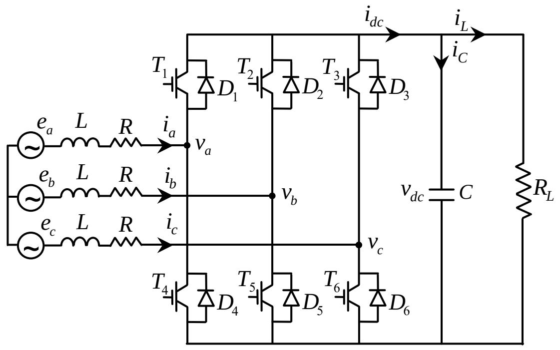


Fig.1. Three-phase PWM rectifier topology.

The mathematical model of the PWM rectifier in the stationary reference frame $\alpha\beta$ can be expressed as follows:

(1) $$e_{\alpha\beta} = Ri_{\alpha\beta} + L\frac{di_{\alpha\beta}}{dt} + v_{\alpha\beta}$$

Where $v_{\alpha\beta}$, $e_{\alpha\beta}$ and $i_{\alpha\beta}$ are voltage vector of the PWM rectifier, voltage vector of the grid and current vector of the grid. R and L are resistance and inductance of smoothing inductor.

On the mains side, the complex apparent power is determined as follows [26]:

(2) $$S = P + jQ = \frac{3}{2}\left(i * e\right)$$

Where "*" indicates the conjugate of a complex vector.

When a three-phase system is sinusoidal and balanced, namely:

(3) $$\frac{de_{\alpha\beta}}{dt} = j\omega e_{\alpha\beta}$$

From (1) to (2), the complex power variation can be derived as follows:

(4) $$\frac{dS}{dt} = \frac{1}{L}\left[\frac{3}{2}\left(\left|e_{\alpha\beta}\right|^2 - \left(v^*_{\alpha\beta} e_{\alpha\beta}\right)\right) - \left(R - j\omega L\right)S\right]$$

The derivative of the active power can be obtained as follows:

(5) $$\frac{dP}{dt} = \frac{3}{2L}\left[\left|e_{\alpha\beta}\right|^2 - \mathrm{Re}\left(v^*_{\alpha\beta} e_{\alpha\beta}\right)\right] - \frac{R}{L}P - \omega Q$$

Similarly, the derivative of reactive power can be obtained as:

(6) $$\frac{dQ}{dt} = \left(-\frac{3}{2L}I_{mg}\left(conj\left(v_{\alpha\beta}\right)e_{\alpha\beta}\right) - \frac{R}{L}Q + \omega P\right)$$

The parameters of the PWM rectifier used in simulation are given in Table 1 [14] [27].

Table 1. PWM-rectifier parameters

The input phase voltage	$V = 125V$ / $f = 50Hz$
The input inductance	$L = 37mH$
The input resistance	$R = 0,3\Omega$
The output capacitor	$C_{dc} = 1100\mu F$
The output voltage	$V_{dc} = 350V$

Design of Model Predictive-DPC

a. Principle of the method studied

The block diagram for the method under study is shown in Fig.2. The rectifier phase voltages and line currents are measured and transformed into the two-phase plane at the beginning of each switching interval. To generate an active power reference value, the output DC bus voltage is measured, compared to a predetermined reference value, and transmitted to an IP controller. The reactive power reference value is set to zero for operation with a unity power factor. To generate the optimal voltage vector v_α and v_β, and for each voltage vector v^k of the converter, the predicted values of the active power P^{k+1} and the reactive power Q^{k+1} are used by the cost function block which compares these predicted values with their reference values P^{ref} and Q^{ref}. The duty cycle block then defines the optimal duration t_v of the active vector which must be added to the zero vector during the control period.

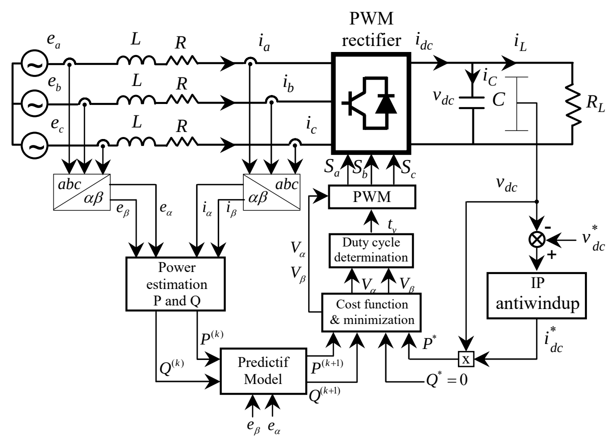


Fig. 2. Control diagram of MP-DPC with duty cycle control.

Active and reactive powers can be calculated from equation (7) and (8):

(7) $$P^k = \mathrm{Re}\left(S\right) = \frac{3}{2}\mathrm{Re}\left(i^*_{\alpha\beta} e_{\alpha\beta}\right)$$

(8) $$Q^k = \mathrm{Im}\,g\left(S\right) = \frac{3}{2}\mathrm{Im}\,g\left(i^*_{\alpha\beta} e_{\alpha\beta}\right)$$

Where k is the current sampling time.

Based on the approach of Euler's method, it is possible to predict the values of active and reactive powers as follows [28]:

(9) $$\frac{dP(t)}{d(t)}=\frac{P(k+1)-P(k)}{T_s}$$

(10) $$\frac{dQ(t)}{dt}=\frac{Q(k+1)-Q(k)}{T_s}$$

Where T_s is the sampling period or control period, $(k+1)$ is the next sampling instant.

By substituting (5) and (6) in (9) and (10) we will have:

(11) $$A=\left(\frac{3}{2L}\left|e_{\alpha\beta}^{k}\right|^2-\mathrm{Re}\left(conj\left(v^k\right)e^k\right)-\frac{R}{L}P^k-\omega Q^k\right)=\frac{P(k+1)-P(k)}{T_s}$$

(12) $$B=\left(-\frac{3}{2L}I_{mg}\left(conj\left(v^k\right)e^k\right)-\frac{R}{L}Q^k+\omega P^k\right)=\frac{Q(k+1)-Q(k)}{T_s}$$

Given that:

(13) $$\begin{cases}Re\left(v_{\alpha\beta}^k e_{\alpha\beta}^k\right)=v_\alpha e_\alpha+v_\beta e_\beta\\ \mathrm{Im}\left(v_{\alpha\beta}^k e_{\alpha\beta}^k\right)=v_\alpha e_\beta-v_\beta e_\alpha\end{cases}$$

So:

(14) $$A=\frac{3}{2L}\left[\left(e_\alpha^2+e_\beta^2\right)-v_\alpha e_\alpha-v_\beta e_\beta\right]-\frac{R}{L}P^k-\omega Q^k$$

(15) $$B=-\frac{3}{2L}\left(v_\alpha e_\beta-v_\beta e_\alpha\right)-\frac{R}{L}P^k-\omega P^k$$

The predicted values of active power and reactive power are expressed as follows:

(16) $$P^{k+1}=P^k+\left(\frac{3}{2L}\left[\left|e^k\right|^2-\mathrm{Re}\left(conj\left(v^k\right)e^k\right)\right]\right)T_s-\left(\frac{R}{L}P^k+\omega Q^k\right)T_s$$

(17) $$Q^{k+1}=Q^k+\left(\frac{-3}{2L}I_{mg}\left(conj\left(v^k\right)e^k\right)\right)T_s-\left(\frac{R}{L}Q^k+\omega P^k\right)T_s$$

The active and reactive powers predicted at the next sampling instant $(k+1)$ can also be calculated using the following equations:

(18) $$P^{k+1}=P^k+AT_s$$

(19) $$Q^{k+1}=Q^k+BT_s$$

The cost function can be expressed as the squared error of the complex power [28]:

(20) $$g=\left(P^{ref}-P^{k+1}\right)^2+\left(Q^{ref}-Q^{k+1}\right)^2$$

Substituting (18) and (19) in (20) we get:

(21) $$g=\left(P^{ref}-P^{k+1}+AT_s\right)^2+\left(Q^{ref}-Q^{k+1}+BT_s\right)^2$$

The minimization problem will be solved as follows:

(22)
$$\begin{cases}\frac{\partial g}{\partial v_\alpha}=-\left(P^{ref}-P^k-AT_s\right)e_\alpha-\left(Q^{ref}-Q^k-BT_s\right)e_\beta=0\\ \frac{\partial g}{\partial v_\beta}=-\left(P^{ref}-P^k-AT_s\right)e_\beta-\left(Q^{ref}-Q^k-BT_s\right)e_\alpha=0\end{cases}$$

By solving the system of equations (23), the mean voltage vector of the converter can be presented by equation (24):

(23) $$\begin{cases}X-\frac{3T_s}{2L}\left(e_\alpha^2+e_\beta^2\right)v_\alpha=0\\ Y+\frac{3T_s}{2L}\left(e_\alpha^2+e_\beta^2\right)v_\beta=0\end{cases}$$

(24) $$\begin{cases}v_\alpha=\frac{2L}{3T_s\left(e_\alpha^2+e_\beta^2\right)}X\\ v_\beta=-\frac{2L}{3T_s\left(e_\alpha^2+e_\beta^2\right)}Y\end{cases}$$

With :

(25) $$\begin{cases}X=\Delta Pe_\alpha+\frac{3T_s}{2L}e_\alpha\left(e_\alpha^2+e_\beta^2\right)-\frac{RT_s}{L}e_\alpha P^k-\omega T_s e_\alpha Q^k\\ \quad\text{-}\Delta Qe_\beta-\frac{RT_s}{L}e_\beta Q^k+\omega T_s e_\beta P^k\\ Y=\Delta Pe_\alpha-\Delta Qe_\beta+\omega T_s\left(e_\alpha P^k+e_\beta Q^k\right)\\ \quad+\frac{RT_s}{L}\left(e_\beta P^k-e_\alpha Q^k\right)-\frac{3T_s}{2L}e_\beta\end{cases}$$

b. Duty cycle control used in MP-DPC

We include the duty cycle control in the MP-DPC to further reduce the power ripple caused by the use of zero voltage vector. The zero voltage vector provides substantially less power variations than the other non-zero voltage vectors. It is possible to combine the zero voltage vector with the non-zero voltage vector to achieve a reduction in the power ripple. The active vector to be applied during a control period is selected by the cost function in (21) and determined by equation (24). The variations in active and reactive power throughout a control period when both an active vector and a zero vector are applied are shown in Fig. 3. The changes in active power (ρ_1 and ρ_2) and the changes in the reactive power (ρ_{11} and ρ_{22}) can be determined from (14) and (15).

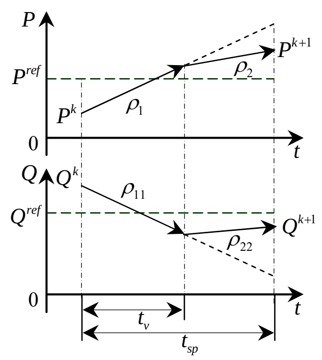


Fig.3. Active and reactive power variations suring one control period.

The active power and reactive power in the next instant $(k+1)$ can be predicted using Fig.3 as follows:

(26) $$P^{k+1} = P^k + \rho_1 t_v + \rho_2 \left(t_{sp}\text{-}t_v\right)$$

(27) $$Q^{k+1} = Q^k + \rho_{11} t_v + \rho_{22} \left(t_{sp}\text{-}t_v\right)$$

The optimal duration t_v of the active vector can be found at the next instant by minimizing the cost function (20). By replacing equations (26) and (27) into (20) and solving equation $\frac{\partial g}{\partial t_v} = 0$, the optimal duration of the best active vector minimization during a control period is determined as follows:

(28) $$t_v = \frac{\left(P^{ref}\text{-}P^{k+1}\right)\left(\rho_1\text{-}\rho_2\right) + \left(Q^{ref}\text{-}Q^{k+1}\right)\left(\rho_{11}\text{-}\rho_{22}\right)}{\left(\rho_1\text{-}\rho_2\right)^2 + \left(\rho_{11}\text{-}\rho_{22}\right)^2} + \dots + \frac{t_{sp}\left(\rho_2^2 + \rho_{22}^2\text{-}\rho_1\rho_2\text{-}\rho_{11}\rho_{22}\right)}{\left(\rho_1\text{-}\rho_2\right)^2 + \left(\rho_{11}\text{-}\rho_{22}\right)^2}$$

The value of t_v is set to zero if $t_v \prec 0$, or t_{sp} if $t_v \succ t_{sp}$.

To obtain the appropriate switching states, knowledge of the voltage sector is required. According to Fig.4, the $\alpha\beta$ frame is divided into six sectors. The number of sectors is determined instantaneously by the position of the voltage vector given by:

(29) $$\theta_n = \arctan\left(\frac{e_\beta}{e_\alpha}\right) \; ; n = 1,\dots,6$$

During a control period, the active vectors obtained by the MP-DPC are applied for the optimal duration t_v, followed by the appropriate zero vectors with minimal switching steps. Taking the following rules, vectors (V_2 V_4, V_6) must be followed by vector V_7, while other vectors (V_1, V_3, V_5), must be followed by vector V_0.

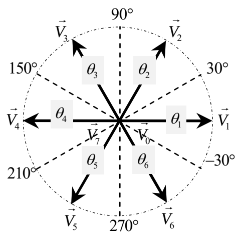
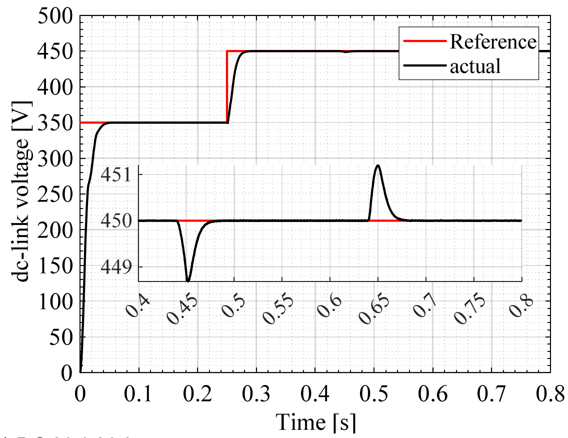


Fig.4. Vector diagram of PWM rectifier

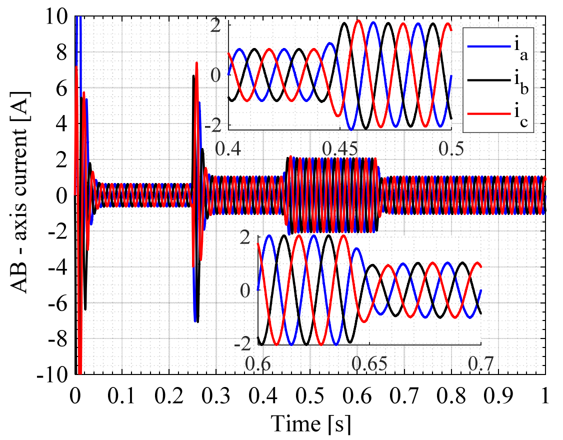
Simulation results and discussion

The MP-DPC of the three-phase PWM rectifier with regulation of the DC bus voltage, based on the previous relations, was implemented on the MATLAB/Simulink software. The simulation results are presented in Fig.5. From Fig.5(a), it can be seen that the DC bus voltage follows its reference correctly and that the load variation does not affect the stability and regulation of the DC bus voltage. It can also be seen that with the proposed approach, the three-phase currents of the grid exhibit a quasi-sinusoidal waveform and are significantly better than those presented in the case of the classical DPC, Fig.5(b). Same remark for the currents in the αβ axes, Fig.5(c). Fig.5(d) shows that the grid current is in phase with the grid voltage thus providing unity power factor. The model predictive DPC control well adjusts the active power in all sectors when changing the load power Fig.5(e), (f). It can also be seen from Fig.5(f), that the reactive power is kept at zero in order to obtain unity power factor. We notice a significant attenuation of the ripples of the active and reactive powers in the case of the MP-DPC control. It can clearly be seen that the MP-DPC achieves decoupled control of active and reactive power and also achieves reduced power ripples and lower current THD while maintaining higher and faster dynamic response. This shows that the proposed analytical approach is quite rigorous.

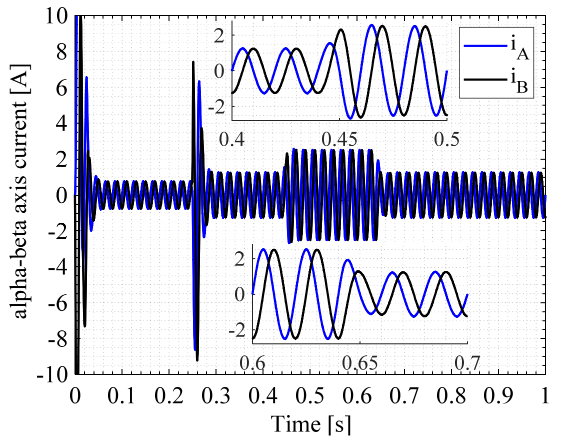
The simulation results obtained both in steady state and in transient are represented by the different curves, they show the feasibility of the MP-DPC approach developed. Good performance is obtained in permanent and transient regimes.



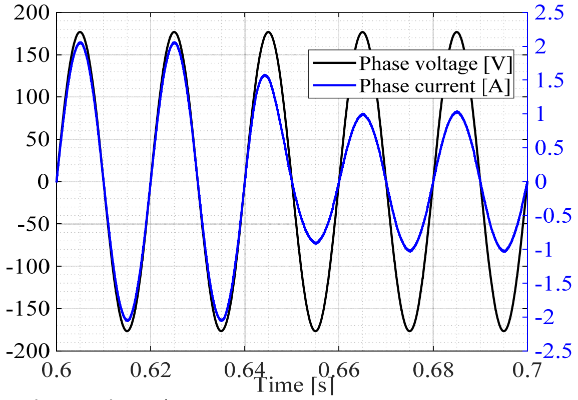
(a) DC-Link Voltage



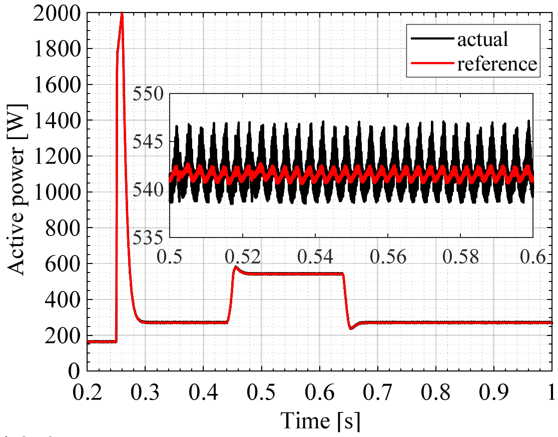
(b) $\alpha\beta$ axix current



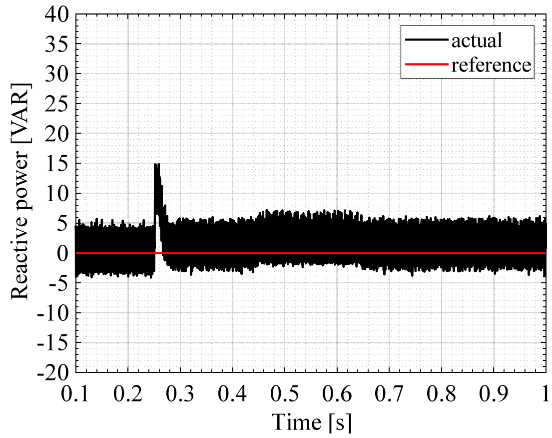
(c) abc axix current



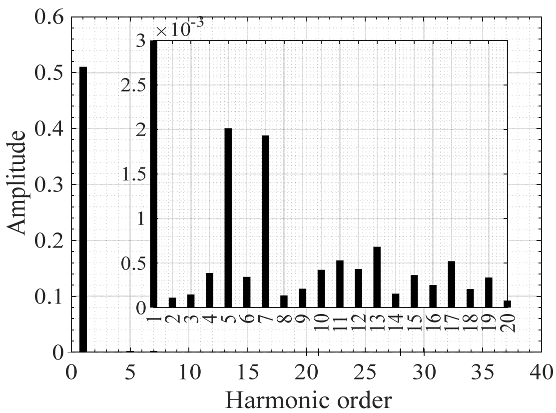
(d) a phase voltage / current



(e) Active power



(f) Reactive power



(g) Current spectral analysis

Fig.5. Simulation results

Conclusion

This work meets the requirements that we have set ourselves, in this case the design of an AC/DC converter capable of both supplying a quality adjustable DC voltage and of taking sinusoidal currents and in phase with the voltages of the electrical network. Based on a predictive model of the power-controlled PWM rectifier, the MP-DPC approach is based on the calculation of an average control vector at the beginning of each sampling period to be applied through the duty cycle control. A mathematical model has been established to predict the future values of active and reactive powers. A better voltage vector has been selected, minimizing a cost function made up of power errors and incorporating the duty cycle. Better steady-state performance in terms of power ripples and current harmonics was achieved. The simulation results showed that the proposed MP-DPC control strategy brought an improvement on the system performance. It makes it possible to obtain a sinusoidal network current and to minimize the ripples for the active and reactive powers.

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