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Performance and High Robustness DPC for PWM Rectifier under Unstable V_{DC} Bus

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ABSTRACT

This paper proposes a strategy de controlling a static AC / DC converter based on direct power control (DPC). The instantaneous active and reactive power is controlled in such a way to ensure the PWM rectifier with a sinusoidal current absorption. This control has proven effective in terms of reduction of total harmonic distortion (THD) of current absorbed. Offers a good control of active and reactive power with an operation at unitary power factor. The test of robustness carried out and the results have proven DPC good performance with strong possibility of de integrate it into the field of high voltage and high power as electric traction.

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1. INTRODUCTION

The principle of direct control was proposed by [1] and was later developed for many applications. The objective was to eliminate the block of modulation and inner loops by replacing a switching table with inputs errors of active and reactive power.

The first application developed was the control of an electrical machine, the control structure was known under the name Control Direct Torque (Direct Torque Control, DTC). In this case, the control stator flux and the electromagnetic torque of the machine without any modulation block [2].

Then, a similar technique called Direct Power Control (Direct Power Control, DPC) was proposed by [4] and developed later by [5] for a PWM rectifier control application in order to improve the quality of the energy electrical network. In this case, the controlled variables are the instantaneous active and reactive power.

Thus, there are two different types of power direct control structures proposed in the literature. On the one hand, references [4], [5] present a non linear control variable switching frequency, better known under the name DPC classic, on the other hand in [6], the author proposes to associate the principle DPC with a pulse width of vector modulation (SVM) in order to obtain a constant switching frequency without the use of a switching table.

Two techniques for performing the calculation of instantaneous power without sensors have been proposed.

The first technique proposed in this paper will be the subject of our work [4], [7], [8] estimates the mains voltages from the values of the voltage of the converter and the RL filter (V-DPC) and establish configurations DPC based on the position of the voltage vector in the stationary α-β reference.

The second technique, developed in [5], [6], [9], [10], the authors propose the estimation of virtual flux as a method for estimating network voltages from the voltages of the converter and the RL filter, (VF-DPC).

This control strategy assures decouples control of active and reactive power, while absorbing sinusoidal currents, ensuring operation of the PWM Rectifier as a clean energy quality with very low THD and power factor equal to unity [11].

We note at the end, that the essential aim of this work is highlighted the importance of this strategy in terms of quality of electric power and in terms of robustness proven by the high performance developed.

2. PRINCIPLE FUNCTIONING OF THE DPC

The (DPC) is based on the direct control of active and reactive power in a PWM rectifier. The errors between the reference values of the instantaneous active and reactive power and their measures are introduced in two hysteresis comparators, which determine, using a switchboard and the value of the sector where the mains voltage are located, the switching status of the semiconductor. The voltage's loop of the DC bus is adjusted with a PI corrector, in order to control the error between the sensed voltage (continuous) and its reference.

The reference reactive power is directly imposed zero for a current's sinusoidal absorption on a source voltage supposed to be sinusoidal, in order ensure the running of the rectifier with a unitary power factor.Figure (1) shows the overall configuration of the direct control of power applied to the rectifier. It is analogous to that of the direct torque control (DTC) of induction machines [12], [13].

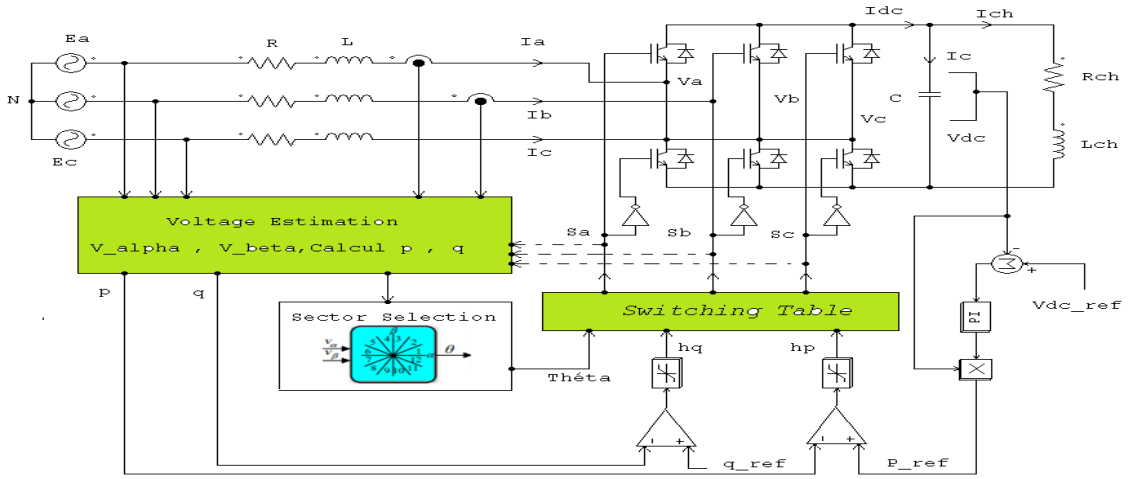


Figure 1. PWM rectifier control block on the network (classical DPC)

The tension and the source currents are measured and transformed by the Concordia matrix, in order to move from a three-phase reference to a fixed two-phase refrence. (α, β).

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{1}$$

The network voltage is estimated by the expression (2)

$$\hat{e}_{a,b,c} = V_{dc}.S_{a,b,c} - L\frac{di_{a,b,c}}{dt} \tag{2}$$

The calculation of the powers, instantaneous active and reactive, is given by the following equations:

$$\begin{cases} p = V_{dc}(S_a i_a + S_b i_b + S_c i_c) - L(\frac{di_a}{dt} i_a + \frac{di_b}{dt} i_b + \frac{di_c}{dt} i_c) \\ q = \frac{1}{\sqrt{3}} \{-U_{dc}[S_a(i_b - i_c) + S_b(i_c - i_a) + S_c(i_a - i_b)] - 3L\left(\frac{di_a}{dt} i_c - \frac{di_c}{dt} i_a\right)\} \end{cases} \quad (3)$$

The knowledge of the estimated voltage sector is required to determine the optimal switching statuses. For this, the work plan (α, β) is divided into 12 sectors. These latter canbede termined by the following relationship: [6]

$$(n-2)\frac{\pi}{6} < \gamma_n < (n-1)\frac{\pi}{6} \quad (4)$$

Where: n= 1…12,
n is the number of the sector instantaneously determined by the the voltage vector's position which is given by:

$$\theta = Arctg \left(\frac{v_\beta}{v_\alpha}\right) \quad (5)$$

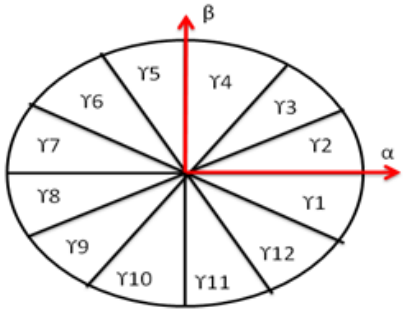


Figure 2. Plan (α, β) divided into 12 sectors

3. CONTROL OF DIRECT VOLTAGE (V_{DC})

Comparing the instantaneous active power at a reference power, this latter is obtained by the DC voltage control block at the capacitor terminals, where we use a PI controller (Proportional, integrator) to control the error between the sensed voltage (continuous) and reference.
Whilst to achieve a unity power factor, reactive power reference is directly imposed zero.

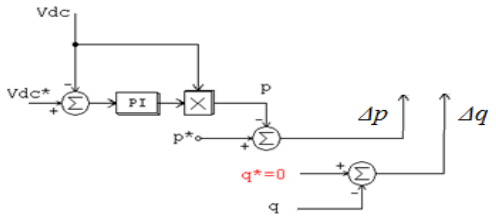


Figure 3. Determination of powers errors (Δp, Δq)

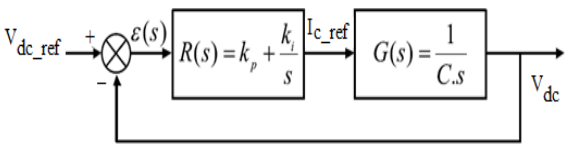


Figure 4. Direct Voltage regulation with PI corrector

Figure 4 shows the regulation of the DC voltage by a PI controller. To control the closed loop system, it is necessary to choose the coefficients k_p *and ki*, in this case we use the imposition method of the poles [6], [14].

$$\begin{aligned} k_p &= 2C\xi\omega_n \\ k_i &= C\omega_n^2 \end{aligned} \tag{6}$$

4. HYSTERESIS CONTROL AND SWITCHING TABLE

The hysteresis control is to keep active and reactive instantaneous power in a desired band. This control is based on two comparators that use as input the error signal between the reference values and estimated values of active and reactive power. If the error is growing and reached the top level, the hysteresis control changes its output to '1', on the contrary if the error signal reaches the lower band, then the output will be switched to '0'.

$$\begin{aligned} Sp = 1 &\Rightarrow p \le p_{ref} - hp \\ Sp = 0 &\Rightarrow p \ge p_{ref} + hp \\ Sq = 1 &\Rightarrow q \le q_{ref} - hq \\ Sq = 0 &\Rightarrow q \ge q_{ref} + hq \end{aligned} \tag{7}$$

The dynamics of active and reactive power can be given as follows :

$$\begin{cases} \dfrac{dp}{dt} = \dfrac{1}{L}(e_\alpha^2 + e_\beta^2) - \dfrac{1}{L}(e_\alpha . u_{e\alpha} + e_\beta . u_{e\beta}) \\ \dfrac{dq}{dt} = \dfrac{1}{L}(e_\alpha . u_{e\beta} - e_\beta . u_{e\alpha}) \end{cases} \tag{8}$$

The synthesis of the switching table is based on the signs of derivatives of active and reactive power in each sector. For each sector, the change of the reactive power is positive for three vectors, negative for three vectors, and zero for V_0, V_7. The sign of change in the active power is positive for four vectors, negative for two or three vectors. For example, for the first sector, the vectors that influence the sign of change of active and reactive power are summarized in the following table [15]:

Table 1. First sector of change of active and réactive power

$\dot{\overline{p}} > 0$	$\dot{\overline{p}} < 0$	$\dot{\overline{q}} > 0$	$\dot{\overline{q}} < 0$	$\dot{\overline{p}} = 0$
V_3, V_4, V_5, V_0	V_1, V_6	V_1, V_2, V_3	V_4, V_5, V_6	V_0, V_7

The switching table proposed for all sectors is presented in the table below

Table 2. All sectors switching table

S_p	S_q	γ_1	γ_2	γ_3	γ_4	γ_5	γ_6	γ_7	γ_8	γ_9	γ_{10}	γ_{11}	γ_{12}
1	0	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4
1	1	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2
0	0	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6
0	1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1

5. SIMULATION AND INTERPRETATION

The simulation was performed to confirm the theoretical study of the rectifier in static mode and check the dynamic performance of the control of powers. Parameters used in simulation are as follows:

- Power source:
  RMS Voltage V = 230 V Frequency f =50 Hz
  Internal resistor Rs = 1 mΩ, Internal inductor Ls = 0.1 mH
- Filter RL :
  L_f =14 mH, R_f= 1.5 Ω
- Rectifier :
  Three-phase bridge rectifier (PD3) to IGBT
- Load:
  Storage capacity C=2mF
  Voltage Reference $V_{DC\text{-}ref}$ = 600 V
  Ohmic load (R= 100 Ω), Inductive load (R=45, L = 50mH), Capacitive load (R=100 Ω, C=200 µF).
- PI controller parameters and hysteresis regulators:
  Sampling frequency Controller PI: fe = 100 kHz
  Band width of hysteresis regulators: h_p= *1 µW*, h_q= *1 µVAR*
  PI controller parameters*:* k_i= *25*, k_p= *1*

5.1. Performance of the DPC During the Variation of the DC Bus

All the figures which follows, shows the response of the rectifier controlled by the DPC when a change of the reference of the DC bus voltage from 600 V to 800 V by a fixed step of 100 V in the moments: 0.4seconds and 0.7seconds.

The value of the reference then descends 550 V at time t = 1seconds and then it goes up to the value of 850 V starting from t = 1.6 seconds (figure 5). The load at the output of the rectifier is of the inductive type (R = 45Ω; L = 50 mH), remains constant during the variation of V_{DC}.

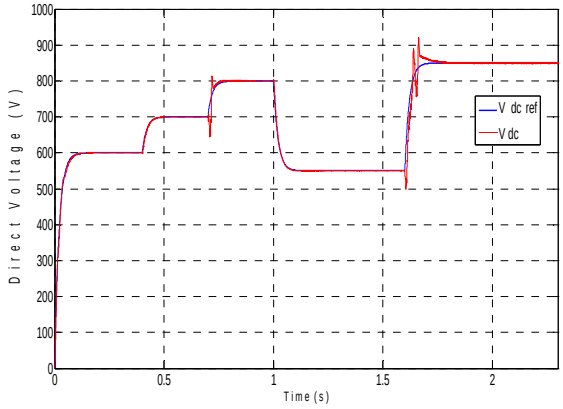


Figure 5. V_{DC} and Reference Voltage during an adjusted variation 600V to 850V

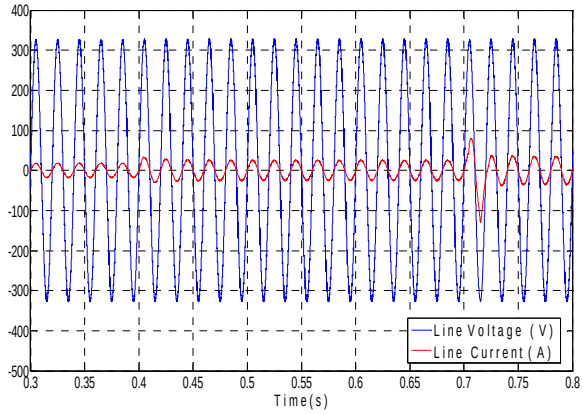


Figure 6. Voltage and line current in the interval Time 0.3s - 0.8s

This variation during the simulation time does not affect the quality of the signals of the electrical quantities.It is noted that the DPC provides a persistent control during disturbances of the DC bus voltage, despite these disturbances, the figures (6 and 7) show that the source current has a sinusoidal shape that changes in amplitude in accordance with the reference changes, harmonic distortion of the current (Figure 8), have very low value (1.53%), which provides a clean power source for electric power quality and unity power factor (Figure 9).

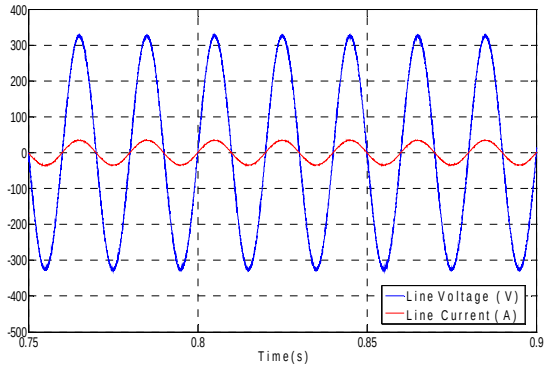


Figure 7. Zoom Current line and Voltage in the interval of time 0.75s - 0.9s

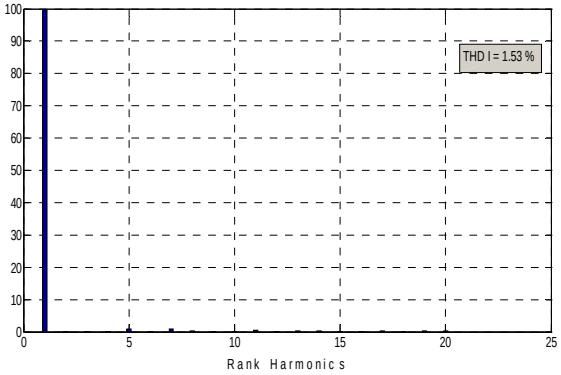


Figure 8. Total Harmonic Distortion of the line current

The instantaneous active and reactive power follow their imposed references with minimal error (Figures 10, 11 and 12), while the reactive power is always zero. By analyzing the results, it is determined that the DPC provides a good dynamic of the system and keeps its robustness despite the imposed disuptions on the reference of the DC bus.

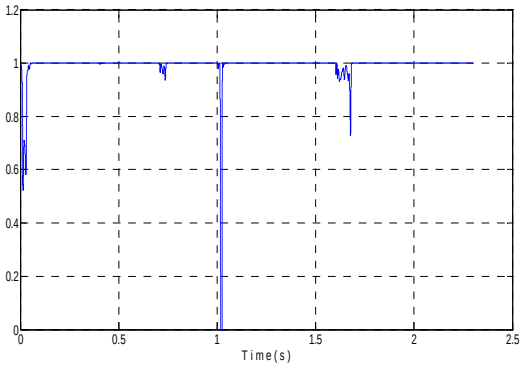


Figure 9. Power Factor

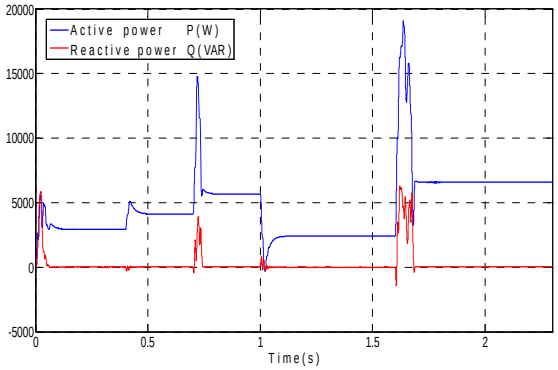


Figure 10. Active and Reactive power depending on the variation of the reference V_{DC}

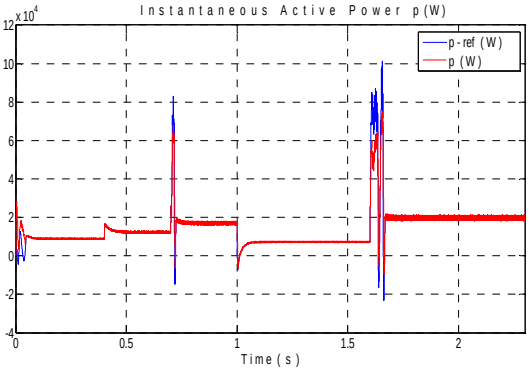


Figure 11. Instantaneous Active Power P (W) and Reference (Pref) during the variation V_{DC}

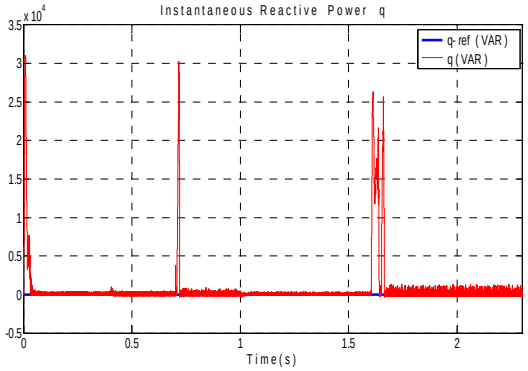


Figure 12. Instantaneous Reactive Power q (VAR) and Reference (q_{ref}) during the variation V_{DC}

5.2. Performances of the DPC During a Load Variation

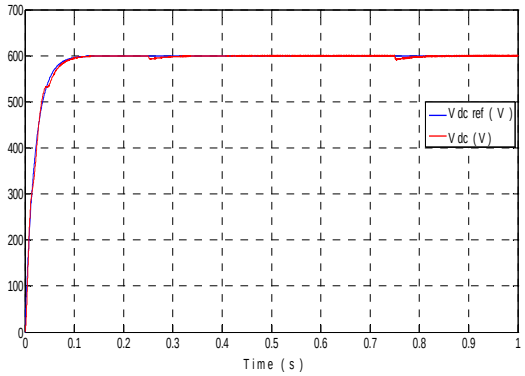


Figure 1.3 Vdc voltage and Vdc_ref during an load Change At time t = 0.25 s and t = 0.75s for V_{DC} = 600 V

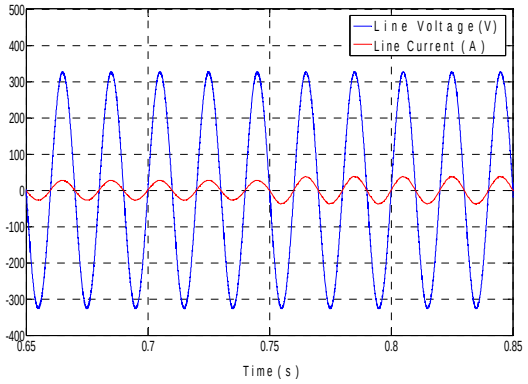


Figure 14. Voltages and line current

For a DC voltage V_{DC} = 600 V maintained constant. At first time, the rectifier feeds an inductive load with a value R = 45 Ω; L = 50mH, we add in parallel in the second time t = 0.25seconds, a capacitive load value (R = 100 Ω, C = 200µF), the we add at the time t = 0.75s a resistive load of R = 100 Ω.
It can be seen from Figures (13, 14, 15) that despite the variation of the load the DC voltage is constant, the current and the voltage source have a sinusoidal shape and have a zero phase shift. The active power evolves in amplitude with the change of the load, while the reactive power is always zero.

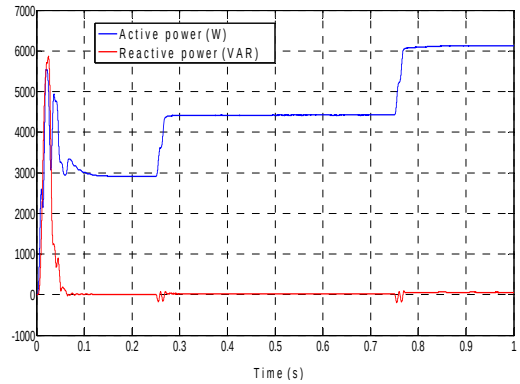


Figure 15. Active and Reactive power during the change load at time t = 0.25 s and t = 0.75s for V_{DC} = 600 V

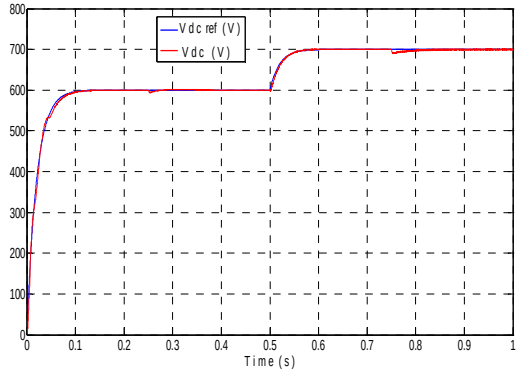


Figure 16. Change the load at time t = 0.25 s for Vdc = 600 V and at time t = 0.75s for V_{DC} = 700V

5.3. Performances of the DPC During an Variation of the DC Bus and the Load

It is noted from Figures (16, 17, 18) that the passage of the continuous voltage of 600 V to 700V at time t = 0.5s and the change of the load to the instant t = 0.25s (R = 100 Ω, C = 200µF) and t = 0.75s (R = 100 Ω), does not affect the performance of the DPC since the reactive power is always zero, the current maintains its shapesinusoidal and evolves with changing load and Vdc, the current phase shift / source voltage is zero, and a unitary power factor .

The active power amplitude naturally reacts with the load current draw and increased V_{DC}.

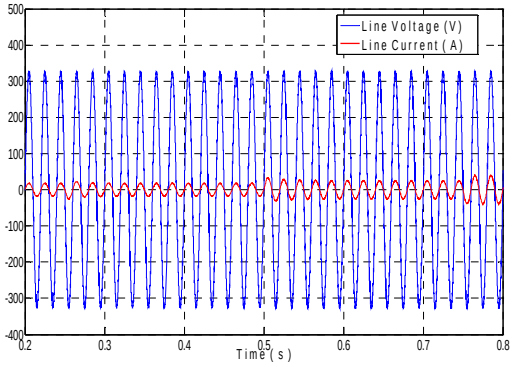


Figure 17. Voltage and line current during the variation of the load and V_{DC}

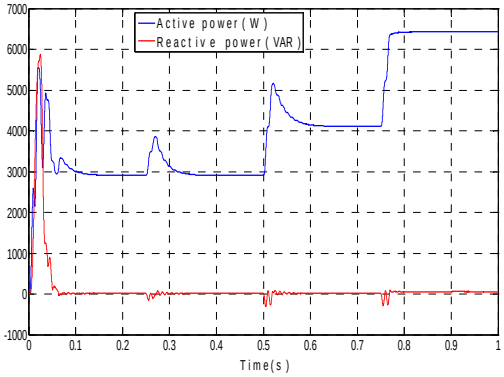


Figure 18. Active and Reactive power depending on theVariation load at time t = 0.25 s and t = 0.75s for a V_{DC} = 600 V and 700 V

5.4. Comment

It remains to point out at the end that this subject was addressed in a way to confirm what has been achieved by the authors [4], [5], [8] by adding a contribution from us which is to implement technical of control (DPC) high performance, characterized by its robustness, efficiency and stability. These performances were achieved and confirmed through the various disturbances created around the energy system, by changing the load and the bus voltage V_{DC}. It remains to be said that this work is characterized by a continuous bus unstable reference during the various tested proposed in this work, which is different from the developed research work and developed by the authors mentioned above.

6. CONCLUSION

The DPC can control the energy exchange between the rectifier and the electrical network with a power factor equal to unity without using a voltage / current sensor.This technique relies on control loops of the instantaneous power and not those currents.Simulation results obtained in this work showed that the direct power control of guarantee reliable control, stable and robust with high dynamic performance, despite the disruptions that has suffered the PWM rectifier.Spectral analysis of the line current obtained by this control strategy shows that all harmonics are attenuated, resulting in a very low THD value of 1.53%, well below the values imposed by international norms (5%).

The DPC provides a quick calculation of instantaneous power that allows obtaining a very high dynamics of the system. It is also characterized by simplicity, not using nested loops (not transformations of coordinated, not modulator).

The results obtained are very promising and high performance, which enables this technique to (DPC), occupied a place of very advanced Among the techniques used to improve power quality and clean up the electrical network

The Performance developed by the DPC during the various tests of robustness, has given to this technique an important place in the field of high voltages and large power such as electric traction. We signal at the end the major disadvantage of the (DPC) is that the converter switching frequency is not constant.

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