Comparative Study of PI and Backstepping with Integral Action Controllers Based on Direct Power Control for Three-Phase PWM Rectifier

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Abstract: The PWM rectifiers are become one of the most used solutions to improve the quality of the electrical energy transfer from a source to a receiver. Indeed, this paper proposes a comparative study of a direct power control (DPC) of three-phase PWM rectifier using backstepping with integral action and Proportional-Integral (PI) controllers for the dc-bus voltage regulation. The evaluation of the robustness and the dynamic performance of these two control techniques have been verified by simulation using Matlab/Simulink environment, under different conditions, such as the variation of the reference voltage and the load. The simulation results show that the direct power control based on backstepping with integral action is more robust than the conventional PI controller and it possesses a good tracking of the reference values and also a more reduced total harmonic distortion (THD).

Keywords: Backstepping with integral action controller; conventional PI controller; PWM rectifier; direct power control

1. Introduction

Since several years, the static converters of power electronics are frequently used in several areas directly affecting the human activities, such as the power supply grid, industrial and domestic areas. Among these converters, we find the diode or thyristor rectifiers which are used in various devices, such as the variable speed drives for asynchronous motors, electric household appliances, computers and their peripherals. They have some advantages namely its simplicity, robustness and a low cost[1]. However, there are also some disadvantages in their use as the distortion of the input currents and the low power factor. The increasing use of these converters in the electrical installations, has significantly contributed to the improvement of their performance. Nevertheless, they constitute one of the main sources of harmonics in the electrical distribution grids. In order to overcome the problems of this rectifiers type, another power converter is developed, called pulse width-modulated (PWM) rectifier. This converter currently constitutes a research axis very important due to its advantages, such as the low harmonic distortion of the line currents, reduced in the size of the filtering devices, and the control of the dc-bus voltage as well as the flow of active and reactive power in the two directions[2]. This shows that the use of this converter family is very promising, on one part it allows functioning quickly with a reduced cost and on the other part it offers the choice of the implementation of the very sophisticated control algorithms[3].

In recent years, several control strategies for three-phase PWM rectifiers have been developed thanks to the advanced development of semiconductor devices and to digital methods[4]. These control techniques have the same goal with a different operating principle; it can be divided into two categories, according to their use of the control loops of the powers and the currents of a three-phase PWM rectifier. In particular, the DPC is based on the direct use of the instantaneous active and reactive power as control variables, by changing the variables of current served in embedded systems[5]. However, it ensured of better dynamic performance as

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well as a regulation of active and reactive power. We find their application in the control of active filters[6] and the PWM rectifier[7]. Another control structure called voltage oriented control (VOC) which allows orienting the absorbed currents vector by the PWM rectifier in the same orientation as that of the line voltages vector[8]-[9]. Moreover, other types of controls are used to control this kind of converter, such as the PI controller[9]-[10] and the nonlinear control based on sliding mode[10]. The present paper propose a comparative analysis of the backstepping with integral action and the Proportional-Integral controllers based on DPC for the three-phase PWM rectifiers, in order to control and stabilizer in an exact way the dc-bus voltage. The paper is organized as follows. Section II presents the mathematical model of three-phase PWM rectifier. The operating principle of DPC comprising all the system is describes in section III. Section IV is devoted to the design of backstepping with integral action controller. Different simulation results of DPC with the two control as well as their interpretations are provided in section V. Finally, the conclusion is drawn in section VI.

2. The mathematical model of three-phase PWM rectifier

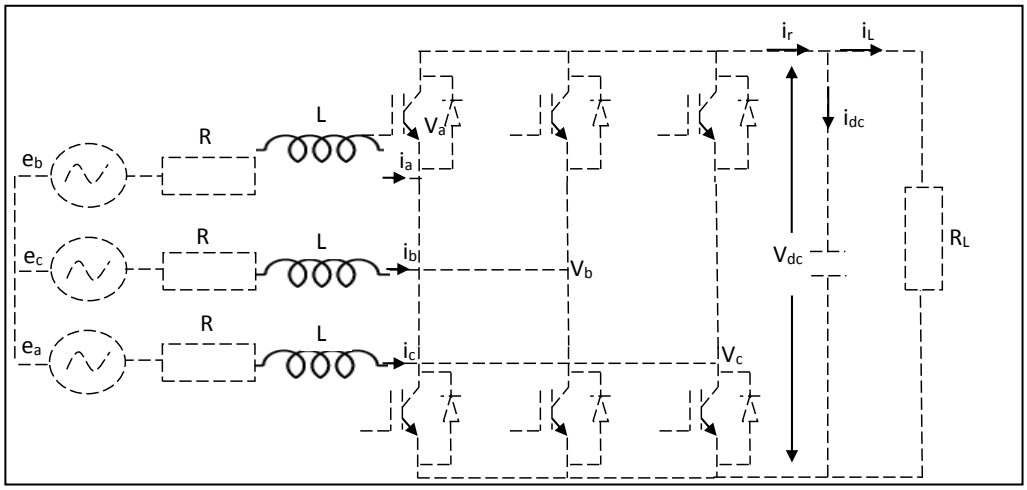

Figure 1. Representative diagram of three-phase PWM rectifier.

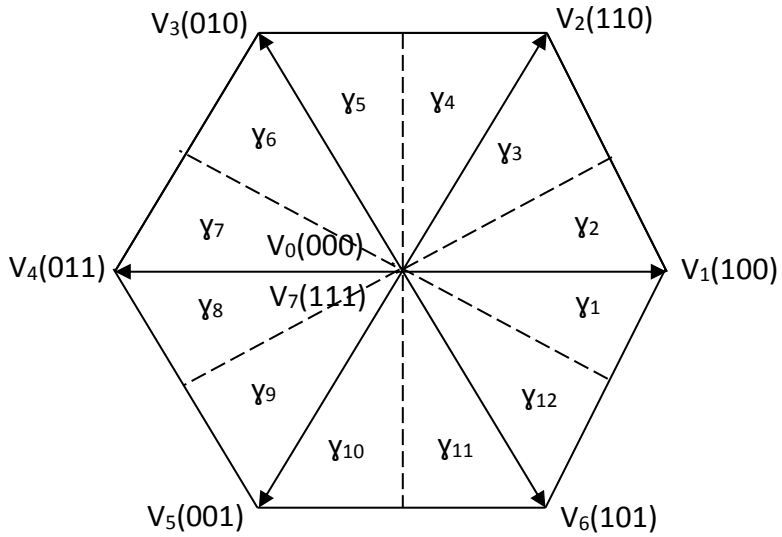

Figure 2. Sectors and voltage vectors of PWM rectifier in (α-β) coordinates.

The structure of three-phase PWM rectifiers is illustrated in Figure. 1. Each phase of this converter is composed of two IGBTs with anti-parallel diode to guarantee the continuity of current. The grid is modeled by a electromotive force three-phase sinusoidal in series with a resistor R and an inductance L on each phase; thus, the load block is composed by a capacitor C put in parallel with an resistance R_L; i_a, i_b and i_c represents the instantaneous line currents; v_a, v_b and v_c are the simple voltages at the converter input.

A three-phase PWM converter is capable of producing eight voltage vectors whose six active vectors (V_1 to V_6) and two inactive vectors (V_0, V_7). The six major vectors are dephased one relative to the other of (π/3). Each vector corresponds to a well-defined sequence composed of three logical variables which instantaneously drive the three arms of the converter[11]. The representation of voltage vectors different of zero in α-β coordinate frame forms a hexagon as shown in Figure 2.

The mathematical model of three-phase PWM rectifier in the (α-β) coordinates is given by:

$$\begin{cases} \dfrac{di_\alpha}{dt} = \dfrac{1}{L}\left(e_\alpha - v_\alpha - Ri_\alpha\right) \\ \dfrac{di_\beta}{dt} = \dfrac{1}{L}\left(e_\beta - v_\beta - Ri_\beta\right) \\ C\dfrac{dv_{dc}}{dt} = S_\alpha i_\alpha + S_\beta i_\beta - i_L \end{cases} \tag{1}$$

With (i_α, i_β), (S_α,S_β) represents respectively the line currents and the rectifier switching states in (α-β) coordinate frame; i_L is the load current.

3. Principles of direct power control for three-phase PWM rectifier

A. System configuration

The DPC is a control technique that uses the instantaneous active and reactive power as control variables, by changing the current variables used in the imbricate systems by a switching table whose inputs are the errors (d_p, d_q) between the reference and measurement values of the instantaneous powers, as well as the voltage vector position (γ_n)[12]. It is equivalent to the direct torque control (DTC) for the electrical machines[13], in which the stator flux and the electromagnetic torque are the quantities controlled. The overall pattern of DPC for a three-phase PWM rectifier is shown in figure 3.

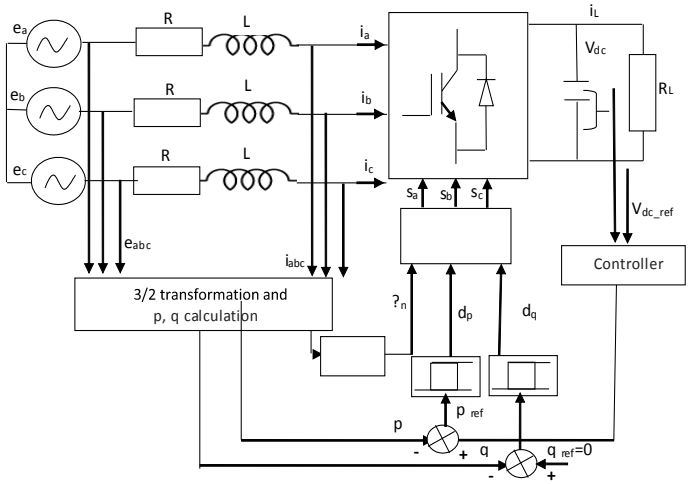

Figure. 3. Schematic diagram of DPC for three-phase PWM rectifier.

The reference of the active power p_{ref} is obtained by regulating the dc-bus voltage V_{dc}. While the reference of the reactive power q_{ref} is set to zero to ensure a unity power factor (UPF) operation. So, the DPC strategy uses the position of the grid voltage vector, for this, the (α-β) plane is divided into twelve sectors, as illustrated in figure. 2. These sectors can be expressed numerically by this expression:

$$(n-2)\frac{\pi}{6} \le \gamma_n \le (n-1)\frac{\pi}{6} \quad \text{n=1,2,…,12} \tag{2}$$

Where n is the sector number.

To establish the switching modes of the bridge rectifier, two hysteresis comparators at two levels are used and allow to establish two logical outputs d_p and d_q from the errors of the instantaneous active and reactive powers by respecting the two following systems:

$$d_p = \begin{cases} 1, & p_{ref} - p \ge H_p \\ 0, & p_{ref} - p \le -H_p \end{cases} \tag{3}$$

$$d_q = \begin{cases} 1, & q_{ref} - q \ge H_q \\ 0, & q_{ref} - q \le -H_q \end{cases} \tag{4}$$

H_p and H_q represent the deviations of hysteresis regulators.

When the digitized values d_p, d_q, and the sector of work γ_n are well determined. The switching states of the three-phase PWM rectifier for all sectors are given by the switching table represented by the table 1:

Table 1. Switching table for DPC

d_p	d_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_6	V_7	V_1	V_0	V_2	V_7	V_3	V_0	V_4	V_7	V_5	V_0
	1	V_7	V_7	V_0	V_0	V_7	V_7	V_0	V_0	V_7	V_7	V_0	V_0
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
	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

B. Determination of instantaneous powers

There are several techniques to determine the instantaneous powers in a three-phase system[12]-[14], such as the measurement of line currents and line voltages. These powers are expressed in the (α-β) stationary coordinates as follows:

$$\begin{cases} p = e_\alpha . i_\alpha + e_\beta . i_\beta \\ q = e_\beta . i_\alpha - e_\alpha . i_\beta \end{cases} \tag{5}$$

At the level of the load block, we have:

$$p = v_{dc} . i_r \tag{6}$$

From (5) and (6), the rectified current i_r is given by:

$$i_r = \frac{e_\alpha . i_\alpha + e_\beta . i_\beta}{v_{dc}} \tag{7}$$

Then, the voltage V_{dc} is determined by substituting the equation (7) in (1), which gives:

$$\frac{dv_{dc}}{dt} = \frac{e_\alpha . i_\alpha + e_\beta . i_\beta}{C . v_{dc}} - \frac{v_{dc}}{C . R_L} \tag{8}$$

4. Design of backstepping with integral action

The backstepping is a control technique of nonlinear systems. It allows to determine constructively the control law of the studied system by the choice of a Lyapunov function[15]. Indeed, the classic backstepping does not correct perfectly the external disturbances. In order to be able to eliminate these errors, we establish a new version of backstepping called backstepping with integral action[16]. This comes back to introduce the integrators into the mathematical model of the system and proceed to applying the conventional backstepping method on this novel model[17].

In order to apply this control method for a three-phase PWM rectifier. The control variable error is defined by the following expression:

$$e_1 = v_{dc\_ref} - v_{dc} \tag{9}$$

The dc-bus voltage tracking error and its dynamic are written as follows:

$$z_1 = e_1 + \delta_1 \int e_1 dt \tag{10}$$

$$\dot{z}_1 = \dot{e}_1 + \delta_1 e_1 \tag{11}$$

The Lyapunov function is defined by:

$$V_1 = \frac{1}{2} z_1^2 \tag{12}$$

The temporal derivative of V_1 is given by:

$$\dot{V}_1 = -k_1 . z_1^2 + z_1 \left[k_1 . z_1 + \dot{v}_{dc\_ref} - \frac{p}{C . v_{dc}} + \frac{i_L}{C} + \delta_1 . e_1 \right] \tag{13}$$

Where k_1 and δ_1 are positive parameters.
The control law is given by the following equation:

$$p_{ref} = \left[k_1 . z_1 + \dot{v}_{dc\_ref} + \frac{i_L}{C} + \delta_1 . e_1 \right] C . v_{dc} \tag{14}$$

We then obtain:

$$\dot{V}_1 = -k_1 . z_1^2 \leq 0 \tag{15}$$

5. Simulation and analysis

In this section, we present the simulations results of our overall circuit shown in Figure. 3. Thus, we analyzed the feasibility and the performance of the backstepping with integral action and the PI controllers based on DPC strategy. These simulation tests have been carried under the same conditions of simulation by using Matlab/Simulink environment.

The parameters used in the simulation are summarized in table 2. The determination of the coefficients K_p and K_i of PI regulator is carried out using pole compensation method.
Table 2. Parameters of the power circuit.

Parameters of circuit	Value
Sampling frequency	10 KHz
Line resistance R	0.25 Ω
Line inductance L	0.01 H
dc-bus capacitor C	2400 µF
Load resistance R_L	100 Ω
Grid phase voltage E	220 V
Source voltage frequency f	50 Hz
dc-bus voltage V_{dc}	600 V

The simulation results obtained in the case of a power supply purely sinusoidal balanced and under a unity power factor operation are given in the Figures. 4, 5, 6, 7, 8 and 9. Indeed, the Figure. 4 and Figure 5 present respectively the simulation results of three-phase PWM rectifier controlled by DPC technique based on backstepping with integral action and PI controllers in case where the reference voltage and the load are fixed ($V_{dc\_ref}=600V$ et $R_L=100\Omega$). From the results of Figure. 4, we observe that the absorbed currents are nearly sinusoidal and the dc-bus voltage is well regulated with good stability and precision compared to the results of Figure. 5. The Figure. 6 and Figure. 7 illustrate respectively the simulation results of DPC obtained in the case where the reference voltage is variable from $V_{dc}=600V$ to $V_{dc}=700V$ at $t=1.4s$, and the load value is set to $R_L=100\Omega$, which causes the variation of the active power without affecting the reactive power, this explains the good control of the instantaneous active and reactive power.

In order to show the effectiveness of the nonlinear controller compared to the PI regulator, we have carried out a series of simulations tests in the case of load decrease from $R_L=100\Omega$ to $R_L=50\Omega$ at t=1.4s, and the reference voltage is set to $V_{dc\_ref}=600V$, this decreasing leads to an augmentation of the line currents as well as a variation of the active power as indicated on the Figure 8 and Figure 9.

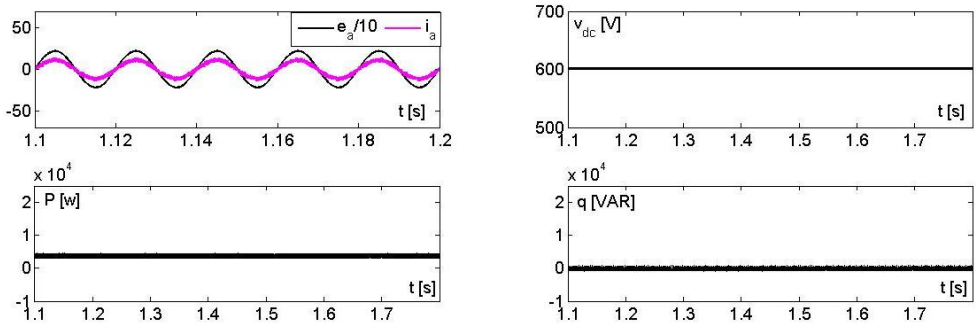

Figure 4. Simulation results of the backstepping with integral action controller based on DPC.

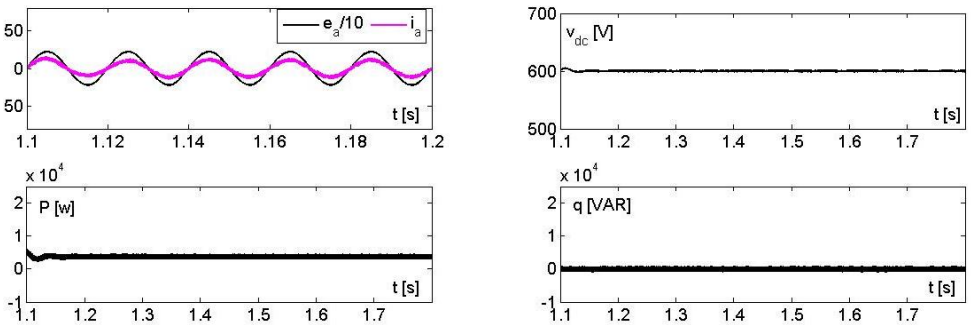

Figure 5. Simulation results of the PI controller based on DPC.

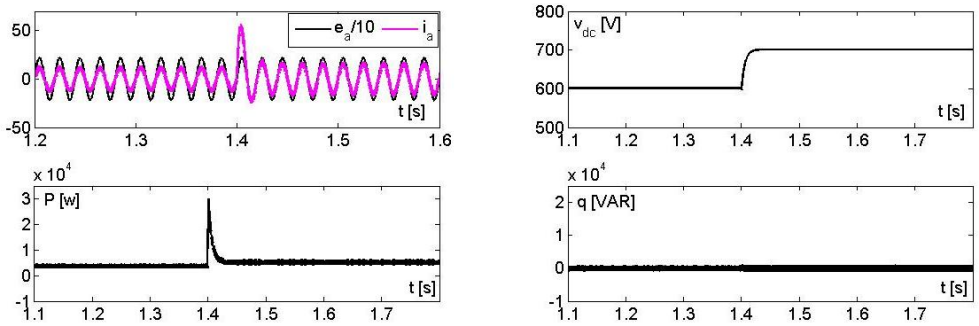

Figure 6. Simulation results of the backstepping with integral action controller based on DPC during the variation of the reference voltage.

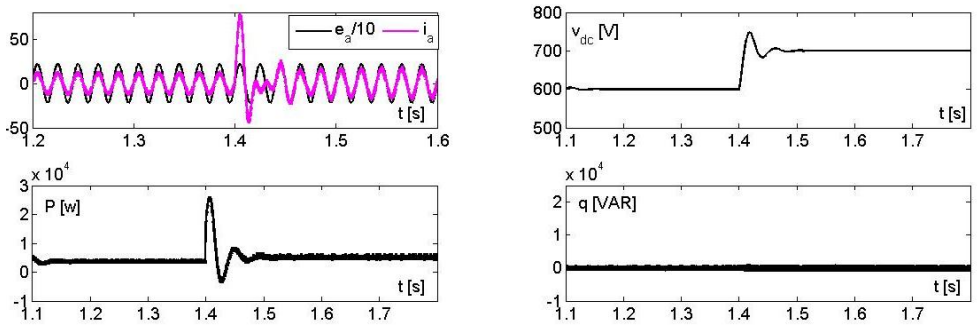

Figure 7. Simulation results of the PI controller based on DPC during the variation of the reference voltage.

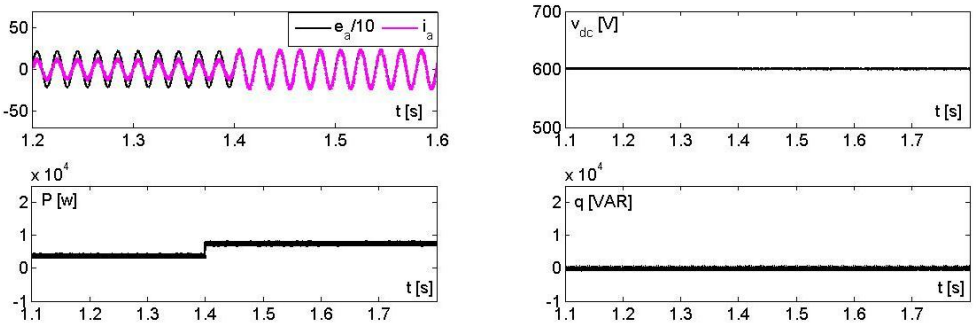

Figure 8. Simulation results of the backstepping with integral action controller based on DPC during the variation of the load.

We note during the simulations tests of the backstepping with integral action controller based on DPC, that the dc-bus voltage and the instantaneous powers present a good tracking to their reference values without any overshoot, static error and with a fast response as well as the absorbed currents are nearly sinusoidal with a reduced total harmonic distortion (THD=1.79%) compared to the linear control PI (THD=2.5%).

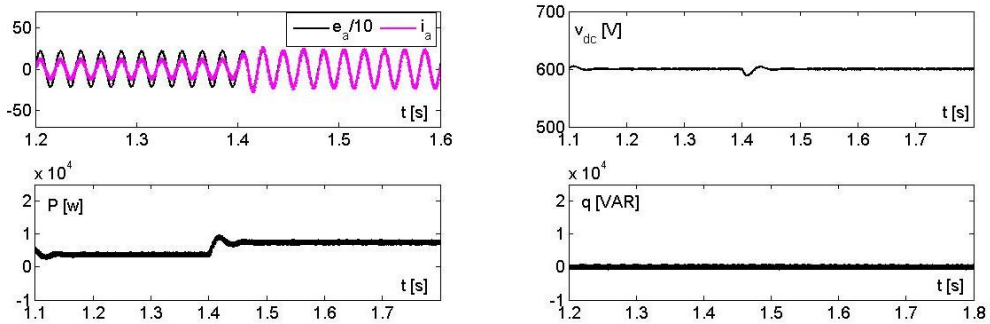

Figure. 9. Simulation results of the PI controller based on DPC during the variation of the load.

6. Conclusion

This work presents a comparative study between the backstepping with integral action and the classical PI controllers based on DPC for three-phase PWM rectifier, whose objective is to show the intake of the two each presented regulators. The analysis of the simulation results obtained has attested the robustness, the effectiveness and the good performance of the backstepping with integral action controller based on the DPC strategy. The advantages provided by this regulator are very important compared to the PI controller especially from the point of view of the harmonic compensation, response time and follow-up of the reference values. It was also noted that this nonlinear regulator has a high-performance for the decoupled control of the instantaneous active and reactive power, and also a better precision of the dc-bus voltage adjustment.

7. References

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