Comparative evaluation of the 5-phase Vienna and the 5-phase PWM rectifiers under DC voltage control

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Abstract

Here a comparative evaluation of the 5-phase Vienna and the 5-phase PWM rectifiers is done. A double closed control loops strategy with an internal current loop and an external voltage loop is investigated. An itemized analysis is performed then the simulations and experimental results are done.

Introduction

In the context of renewable energy source exploitation, the fault-tolerant energy conversion chains is an attractive solution. Compared to the classic association of a 3-phase PWM rectifier with conventional three-phase machine, the polyphase electrical drives offers many advantages [1]-[4]. Many research works investigate the DC bus control strategies of the Vienna rectifier and the PWM rectifier as in [5]-[7]. Compared to others rectifiers, VIENNA rectifier presents more advantages. It is the favorite choice for its advantages such as less numbers of the switches, simple structure, high power density and ability to realize unity power factor with appropriate control strategy. The drawback of the VIENNA rectifier is the neutral-point (NP) voltage unbalance and oscillation [8]-[9]. Here a comparative evaluation of the 5-phase Vienna and the 5-phase PWM rectifier, In the context of renewable energy source exploitation, is done. This converters are supplied by the 5-phase PMSG non-sinusoidal EMF. The 5-phase Vienna rectifier compared to the 5-phase PWM rectifier has several advantages. Its particularity is that it has 5 active power components combined with diodes so it is deemed to be robust. In [10] the comparison to the Vienna rectifier with the conventional PWM rectifier show that the switching losses are reduced by a factor of 6 for frequencies below to 50 kHz. Another advantage of the Vienna rectifier, in the context of renewable energy source exploitation, is its non-reversibility. Fig. 1 et Fig. 2 show respectively the control scheme of the 5-phase PWM rectifier supplied by the 5-phase PMSG and the control scheme of the 5-phase Vienna rectifier supplied by the 5-phase PMSG.

This work focuses on the DC bus voltage control performances of the two rectifiers and the current control performances of the 5-phase PMSG. The operation in V-f mode is considered. The generator speed is considered constant. The inverter, located after the DC bus regulates the voltage across the load. The converter, generator side, regulates the DC bus voltage and the power transfer. The power delivered by the generator is imposed by the load. Here the inverter – load set can be replaced by a single-phase load purely resistive. the generator speed being considered constant, the DC bus voltage regulator generates the torque reference which permits to calculate the current references. Many current control strategy of 5-phase permanent magnet synchronous machine have already been proposed in [11]-[15]. Here, all harmoninics of the EMF is exploited.

The DC bus voltage is controlled on the generator side by controlling the electromagnetic torque of the 5-phase PMSG non sinusoidal EMF. The controller for the regulation the DC bus voltage is a conventional PI regulator. In the abcde frame, the current references is not constant. Then a robust and accurate AC current controller which also controls the switching frequency of the power switches and is slightly sensitive to the system's electrical parameters is necessary as proposed in [15]-[20]. For a good comparison, the machine neutral is connected to the midpoint of the DC bus for both rectifers. An itemized analysis is done. Simulation and experimental results are presented.
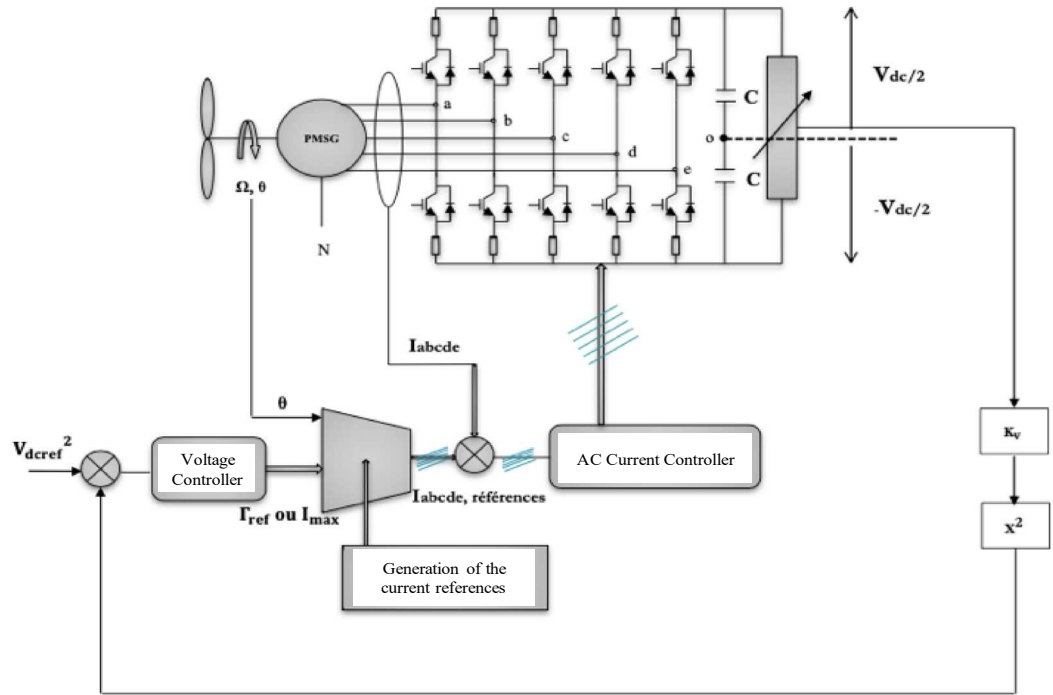
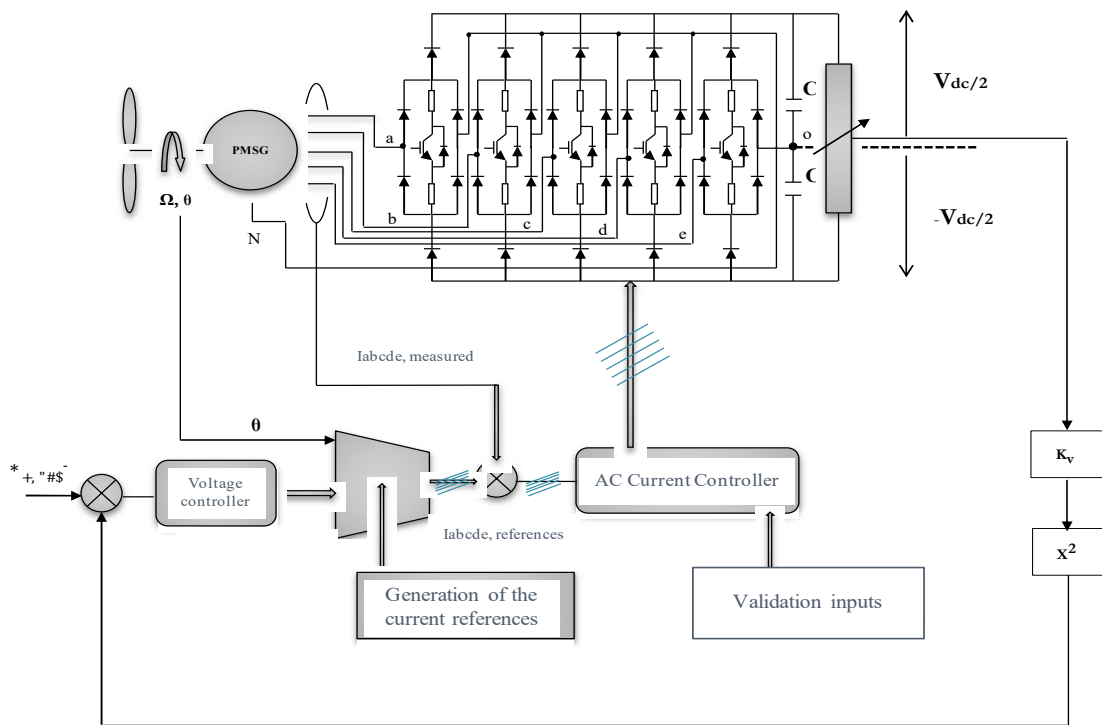**Fig. 1: DC voltage Control scheme of the 5-phase PWM rectifier supplied by the 5-phase PMSG non sinusoidal EMF**

Fig. 2: DC voltage Control scheme of the 5-phase Vienna rectifier supplied by the 5-phase PMSG non sinusoidal EMF

Electrical model of the Two converters and the 5-phase PMSG

Electrical model of the 5-phase PMSG – PWM rectifier SET

The electrical model of the 5-phase PMSG – PWM rectifier is given by:

$$[E] = [R][I] + [L]\frac{d}{dt}[I] + [T_T][S_T]\frac{V_{dc}}{2} + \frac{1}{5}E_t[I_5] \tag{1}$$

where $[S_T] = \begin{bmatrix} S_a \\ S_b \\ S_c \\ S_d \\ S_e \end{bmatrix}$ $[I] = \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_d \\ I_e \end{bmatrix}$ $[E] = \begin{bmatrix} E_a \\ E_b \\ E_c \\ E_d \\ E_e \end{bmatrix}$

$$[T_T] = \frac{1}{5}\begin{bmatrix} 4 & -1 & -1 & -1 & -1 \\ -1 & 4 & -1 & -1 & -1 \\ -1 & -1 & 4 & -1 & -1 \\ -1 & -1 & -1 & 4 & -1 \\ -1 & -1 & -1 & -1 & 4 \end{bmatrix} \quad [R] = \begin{bmatrix} r & 0 & 0 & 0 & 0 \\ 0 & r & 0 & 0 & 0 \\ 0 & 0 & r & 0 & 0 \\ 0 & 0 & 0 & r & 0 \\ 0 & 0 & 0 & 0 & r \end{bmatrix} \quad [L] = \begin{bmatrix} L_1 & L_2 & L_3 & L_3 & L_2 \\ L_2 & L_1 & L_2 & L_3 & L_3 \\ L_3 & L_2 & L_1 & L_2 & L_3 \\ L_3 & L_3 & L_2 & L_1 & L_2 \\ L_2 & L_3 & L_3 & L_2 & L_1 \end{bmatrix}$$

$[I_5] = \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}$ and $E_t = E_a + E_b + E_c + E_d + E_e$

S_z represents the conduction status of the branch supplying the z-phase (1 or -1 depending on the switches status), $z = a, b, c, d, e$.

The dynamic model of the 5-phase PMSG in abcde frames is developed in [2][15].

Electrical model of the 5-phase PMSG – Vienna rectifier SET

In contrary to the classic PWM rectifier, the equivalent model of the 5-phase Vienna rectifier is a complex. Establishing the equivalent model of the Vienna rectifier requires to know the conduction states of each diode. The control strategy adopted under normal operation requires that the current and FEM vectors are collinear. In this case, it is possible to not consider the conduction status of each diode of the Vienna rectifier. The electrical model of the 5-phase PMSG – Vienna rectifier is simple. If the neutral of the machine is not connected, the relation which links the generator simple voltages to the Vienna output voltages can be written in the form:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix} = \frac{1}{5}\frac{V_{dc}}{2}\begin{bmatrix} 4 & -1 & -1 & -1 & -1 \\ -1 & 4 & -1 & -1 & -1 \\ -1 & -1 & 4 & -1 & -1 \\ -1 & -1 & -1 & 4 & -1 \\ -1 & -1 & -1 & -1 & 4 \end{bmatrix}\begin{bmatrix} (1 - S_a)\text{sign}(i_a) \\ (1 - S_b)\text{sign}(i_b) \\ (1 - S_c)\text{sign}(i_c) \\ (1 - S_d)\text{sign}(i_d) \\ (1 - S_e)\text{sign}(i_e) \end{bmatrix} + \frac{1}{5}E_t[I_5] \tag{2}$$

where $[I_5] = \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}$ and $E_t = E_a + E_b + E_c + E_d + E_e$

Sz represents the conduction status of the branch supplying the z-phase (1 or -1 depending on the switches status), $z = a, b, c, d, e$.

Therefore, the electrical model of the 5-phase PMSG – Vienna rectifier is given by:

$$[E] = [R][I] + [L]\frac{d}{dt}[I] + [T_T][S_{TV}]\frac{V_{dc}}{2} + \frac{1}{5}E_t[I_5] \tag{3}$$

where $[S_{TV}] = \begin{bmatrix} (1 - S_a)\text{sign}(i_a) \\ (1 - S_b)\text{sign}(i_b) \\ (1 - S_c)\text{sign}(i_c) \\ (1 - S_d)\text{sign}(i_d) \\ (1 - S_e)\text{sign}(i_e) \end{bmatrix}$ $[I] = \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_d \\ I_e \end{bmatrix}$ $[E] = \begin{bmatrix} E_a \\ E_b \\ E_c \\ E_d \\ E_e \end{bmatrix}$

$$[T_T] = \frac{1}{5}\begin{bmatrix} 4 & -1 & -1 & -1 & -1 \\ -1 & 4 & -1 & -1 & -1 \\ -1 & -1 & 4 & -1 & -1 \\ -1 & -1 & -1 & 4 & -1 \\ -1 & -1 & -1 & -1 & 4 \end{bmatrix} \quad [R] = \begin{bmatrix} r & 0 & 0 & 0 & 0 \\ 0 & r & 0 & 0 & 0 \\ 0 & 0 & r & 0 & 0 \\ 0 & 0 & 0 & r & 0 \\ 0 & 0 & 0 & 0 & r \end{bmatrix}$$

$$[L] = \begin{bmatrix} L_1 & L_2 & L_3 & L_3 & L_2 \\ L_2 & L_1 & L_2 & L_3 & L_3 \\ L_3 & L_2 & L_1 & L_2 & L_3 \\ L_3 & L_3 & L_2 & L_1 & L_2 \\ L_2 & L_3 & L_3 & L_2 & L_1 \end{bmatrix}$$

If the neutral of the machine is connected to the DC bus midpoint, equation (2) becomes :

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix} = \frac{V_{dc}}{2}\begin{bmatrix} (1 - S_a)\text{sign}(i_a) \\ (1 - S_b)\text{sign}(i_b) \\ (1 - S_c)\text{sign}(i_c) \\ (1 - S_d)\text{sign}(i_d) \\ (1 - S_e)\text{sign}(i_e) \end{bmatrix} \tag{4}$$

Thus the electrical model of the 5-phase PMSG – Vienna rectifier can be written:

$$[E] = [R][I] + [L]\frac{d}{dt}[I] + [S_{TV}]\frac{V_{dc}}{2} \tag{5}$$

DC Voltage Control strategy

This part is developed in [19].
The Fourier analysis of the EMF of the machine under consideration is summarized in Table 1. Table 1 summarizes the normalized magnitude of each harmonic of the considered machine.

Table 1. Fourier analysis of the EMF profile

EMF Harmonic	1	3	7	9
Magnitude/Fundamental %	100%	30%	0.2%	0.7%

The Fourier analysis of the EMF shows that the ninth harmonic and the seven harmonic are very low and can be neglected. Then the fundamental and the third harmonic of EMF are only considered. In this part a control strategy to keep the DC bus voltage constant is developed. neglecting all losses and applying the principle of power conservation, we can write:

$$P \approx P_{dc} + P_{ch} \approx V_{dc}I_c + P_{ch} \tag{6}$$

P : the generator electromagnetic power
P_{ch} : the power available across the load
V_{dc} : the DC voltage across the load
I_c : the current flowing through the equivalent capacitor
P_{dc} : the power received by the equivalent capacitor
C_{eq} : the equivalent capacitor

By replacing the expression of the generator electromagnetic power, the following equations are deduced:

$$C_{eq}V_{dc}\frac{dV_{dc}}{dt} = \Gamma\Omega - \Gamma_0\Omega \tag{7}$$

$$V_{dc}^2(s) = \frac{2\Omega}{C_{eq}s}(\Gamma - \Gamma_0) \tag{8}$$

The seven harmonic is very low and is neglected. The spectrum of the current references is reduced to the fundamental and to the third harmonic. We show that the expression of the electromagnetic power is given by [15]:

$$P = [E]^t[I] = \frac{5}{2}(E_mI_m + E_sI_s) \tag{9}$$

Where
E_m and E_s are respectively the maximum magnitude of the EMF fundamental and the EMF third harmonic

I_m and I_s are respectively the maximum magnitude of the current fundamental and the current third harmonic So, Equation (8) can be rewritten in the form:

$$V_{dc}{}^2(s) = \frac{5E_m(1+x^2)}{C_{eq}s}(I_m - I_0)$$ (10)

where $x = \frac{I_s}{I_m} = \frac{E_s}{E_m}$ (the average torque is maximized and the copper losses is minimized [15])

Generation of the optimal current references

This part is developed in [15]. The power transfer is optimal when the losses are minimal. In this case an optimal control strategy that minimizes the reactive power and the copper losses is proposed. The fundamental and the third harmonic EMF are only considered.

In this case the E_a, E_b, E_c, E_d, E_e expressions are written:

$$[E] = \omega\Phi_m[G(\theta)] + 3\omega\Phi_s[G(3\theta)]$$ (11)

Where :

$$[G(\theta)] = \begin{bmatrix} A(\theta) \\ B(\theta) \\ C(\theta) \\ D(\theta) \\ E(\theta) \end{bmatrix} = \begin{bmatrix} \sin(\theta) \\ \sin\left(\theta - \frac{2\pi}{5}\right) \\ \sin\left(\theta - \frac{4\pi}{5}\right) \\ \sin\left(\theta - \frac{6\pi}{5}\right) \\ \sin\left(\theta - \frac{8\pi}{5}\right) \end{bmatrix} \quad [G(3\theta)] = \begin{bmatrix} A(3\theta) \\ B(3\theta) \\ C(3\theta) \\ D(3\theta) \\ E(3\theta) \end{bmatrix} \begin{bmatrix} \sin(3\theta) \\ \sin3\left(\theta - \frac{2\pi}{5}\right) \\ \sin3\left(\theta - \frac{4\pi}{5}\right) \\ \sin3\left(\theta - \frac{6\pi}{5}\right) \\ \sin3\left(\theta - \frac{8\pi}{5}\right) \end{bmatrix}$$

Where Φ_m, Φ_s are respectively the maximum magnitudes of the flux in the main and in the secondary machine, $\omega = p\Omega$ is the electrical angular speed and p is the number of pair poles and it is equal to 3 for the considered machine.

The total optimal current reference for each phase is given by [15] :

$$I_{zref} = \frac{E_z}{\sum_{z=a}^{e} E_z{}^2}\Gamma_{ref}\Omega$$ (12)

The self-oscillating phase-shifted modulator and current controller [20]

The next figure shows a basic scheme where the chosen current controller has been used in DC/AC converters [17][18]. It runs in sliding mode and offers an accurate current control. At high and low frequencies, it operates in different ways, i.e. at high frequency it operates for frequency switching control and at low frequency it operates for current control.
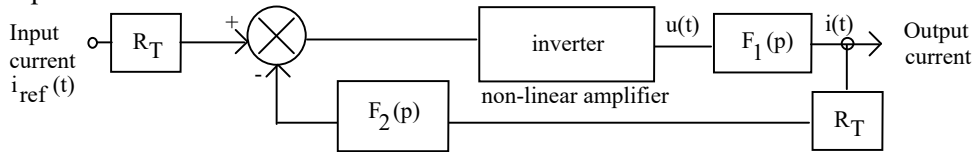

Figure 3: Scheme of the inverter current control loop

The control loop is used to create a current to voltage feedback. The inverter feeds the voltage signal u(t) to the load. Then, the transfer functions F1(p), F2(p) and RT respectively depict the load voltage to current transfer function, a second order low-pass filter transfer function and a current sensor transfer one.

$$F_1(p) = \frac{I(p)}{U(p)} = \frac{1}{R_L + L_L p}$$ (13)

$$F_2(p) = \frac{1}{1 + 2\xi\dfrac{p}{\omega_0} + \dfrac{p^2}{\omega_0^2}}$$ (14)

Thanks to the third order low-pass transfer function, the linear part gives birth to a self-oscillating mode. Then, the maximum switching frequency of the power switches depends on the f_{osc} oscillation frequency given by [17][18].

$$\frac{f_{osc}}{f_0} = \frac{\omega_{osc}}{\omega_0} = \sqrt{1 + \frac{2\xi}{\omega_0 \tau_1}} = \sqrt{1 + 2\xi . \frac{f_{c1}}{f_0}} \qquad (15)$$

It is the peculiarity of this current controller which thus limits the maximum switching frequency to a known value. Moreover, an equivalent gain of the non-linear stage, i.e. the inverter, can be defined. It is done in [17].

Simulations and Experimental results

This work focuses on the DC bus voltage control performances of the Two rectifier and the current control performances of the 5-phase PMSG. The generator speed is constant. Simulations are carried out using Matlab Simulink. The experimental prototype used to validate the proposed control strategy involves a 3 kW DC machine, 3kW 5-phase PMSG, 5-phase PWM rectifier, a 4 quadrant inverter which controls the DC machine in order to keep the generator speed constant and a dspace 1103.
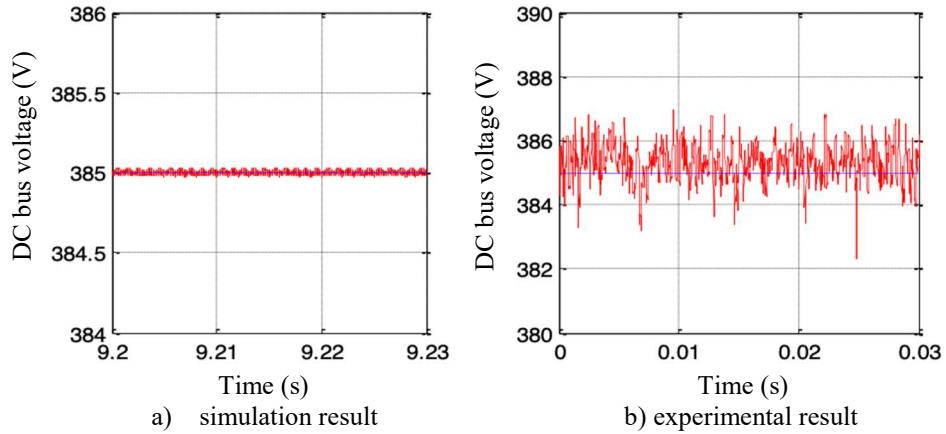

a)   simulation result   b) experimental result

Fig. 4: PWM rectifier, DC bus Voltage
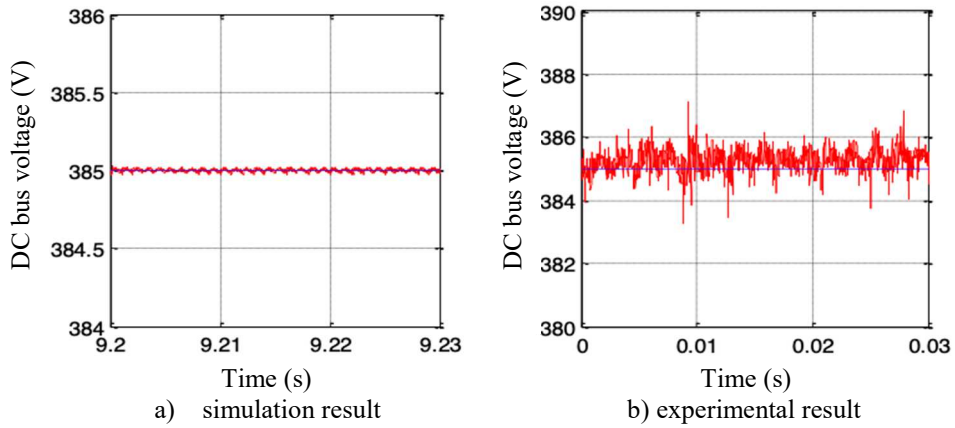

a)   simulation result   b) experimental result
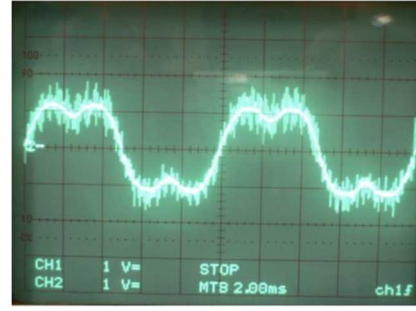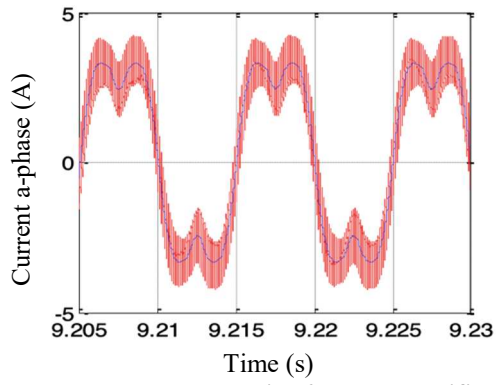
Fig. 5: Vienna rectifier, DC bus Voltage

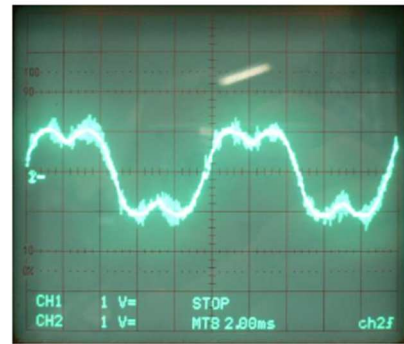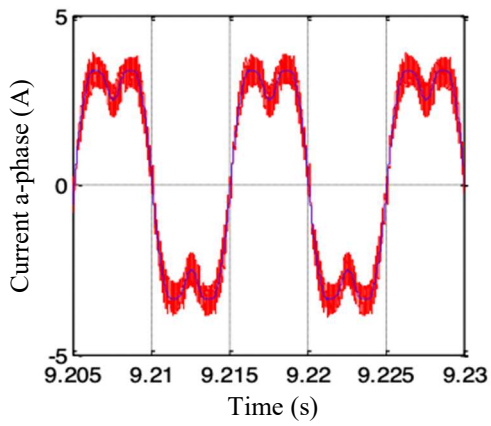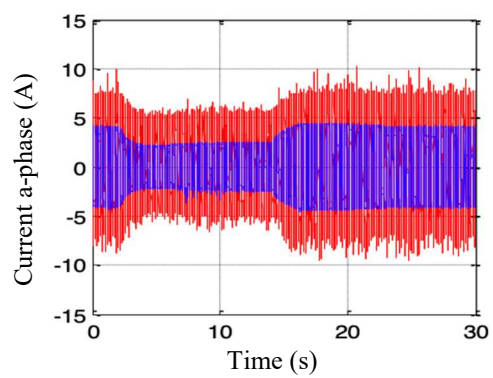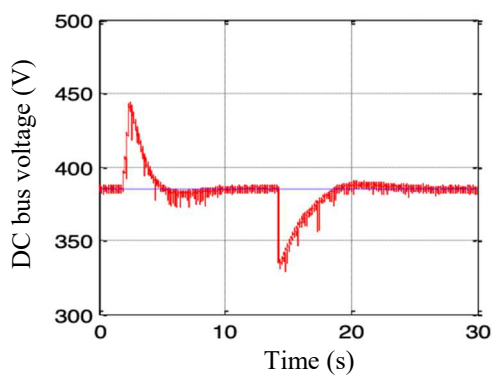**Fig. 6: PWM rectifier, Current in the a-phase**

Fig. 7: Vienna rectifier, Current in the a-phase

a) DC Bus Voltage   b) Current in the a-phase

Fig. 8: PWM rectifier, Load impact 50 %, experimental result

Fig. 4, Fig. 5, Fig. 6 and Fig. 7 show the simulation and experimental results in the case of the closed loop voltage control. The seventh harmonic of the FEM is exploited. The developed control strategy made it possible to regulate the DC bus voltage (Fig. 4 and Fig. 5). Even with a 50% load impact, the DC bus voltage stabilizes at his reference value (Fig. 8). Without the measurement noises and the switching effect, no disturbance has been observed. Fig. 6 and Fig. 7 show a good tracking performance of AC current controller used to control the imposed sinusoidal current in abcde frame.

Now, the performances of the 5-phase Vienna rectifier and the 5-phase PWM rectifier are compared. All simulated results are in accordance with the experimental results. By viewing Fig. 6 and Fig. 7, current ripples are very high in the case of the 5-phase PWM rectifier. The ripple amplitude of the DC output voltages is lower when using the 5-phase Vienna rectifier in comparison with the 5-phase PWM rectifier as shown in Fig. 4 and Fig. 5.

Conclusion

A comparative evaluation of the 5-phase Vienna and the 5-phase PWM rectifier has been done. Simulation and experimental results prove the effectiveness of the developed DC bus voltage control strategy. All simulated results are in accordance with the experimental results. In conclusion, the analysis has shown that the current ripples and the ripple amplitude of the DC output voltages is lower when using the 5-phase Vienna rectifier.

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