

# Comparative Study of Wind Energy Conversion System Driven by Matrix Converter and AC/DC/AC Converter

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**Abstract**—In this work we presents comparative study of a variable speed wind energy conversion system (WECS) based on the doubly fed induction generator (DFIG) driven by two AC/DC/AC converters and WECS driven by matrix converter (MC). The whole system is presented in d-q-synchronous reference frame. For this purpose, the control of the active and reactive power using PI controller is verified using software Matlab/Simulink, studies on a 1.5 MW DFIG wind generation system. Simulation results obtained are presented and analyzed. The results show the high performance and improve the electric energy of the control strategy adopted in the WECS based on a DFIG driven by a MC.

**Index Terms**-- wind systems, doubly fed induction generator, matrix converter, Simulation.

## NOMENCLATURE

$P_s, Q_s$	stator active and reactive power
$P_r, Q_r$	rotor active and reactive power
$T_{em}$	DFIG electromagnetic torque (N m)
$d, q$	synchronous reference frame index
$V_{sd,q}$	stator d-q frame voltage
$V_{rd,q}$	rotor d-q frame voltage
$i_{sd,q}$	stator d-q frame current
$i_{rd,q}$	rotor d-q frame current
$\varphi_{sd,q}$	stator d-q frame flux
$\varphi_{rd,q}$	rotor d-q frame flux
$R_s, R_r$	stator and rotor Resistances
$L_s, L_r$	stator and rotor self Inductances
$L_m$	mutual inductance
$\omega_s, \omega_r$	synchronous and rotor angular frequency
$\rho$	air density
$V$	wind speed
$R$	rotor radius
$\lambda$	tip-speed ratio
$\Omega_{tur}$	aeroturbine rotor speed
$\Omega_m$	generator speed
$G$	gearbox ratio
$J$	turbine total inertia
$\sigma$	coefficient of dispersion.
$q$	demand voltage ratios
$V_{is}$	peak input voltage
$\omega_i$	angular frequencies of input voltage
$\omega_o$	angular frequencies of output voltage

## 1. INTRODUCTION

In the aim to the nature conservation and the biodiversity maintaining of natural environments, the world is heading more and more towards renewable energy for electricity production. Wind power is one of the cleanest sources of renewable energy that allow producing the green energy. However, wind energy is a natural resource that features many advantages since while producing electricity they do not propagate any gas greenhouse effect, do not degrade the quality of the air and do not pollute nor the soils or waters. Furthermore, it do not produce toxic or radioactive waste [1-5]. Nowadays, wind generation system based on a doubly fed induction generator (DFIG) are employed widely in large wind farms fat has its many advantages [5-12]. The conventional WECS is constituted of the turbine, the gearbox and the DFIG. The DFIG is connected directly to the grid via its stator but also via its rotor by means of two static converters to allow an exchange of energy between the network and the DFIG at the speed of synchronism. The rotor-side converter (RSC) and the grid-side converter (GSC) are connected back-to-back by a dc-link capacitor. These converters are controlled by Pulse Width Modulation (PWM) [9]. So, for remedy the use of two converter and to reduce maintenance, cost and number of components, the matrix converter (MC) can be used for a direct AC/AC conversion without dc-link connection [13-17]. The MC is widely employed in large wind farms that have many advantages: direct power converter AC/AC, bi-directional power flow, nearly sinusoidal input and output waveform, and allows to control: the rotor currents magnitude, frequency and input power factor. [15, 17]. MC has three important topologies [18, 19]: AC controller topology, cyclo-converter topology and matrix converter topology. For such several advantages, the MC has generated a considerable attentions and curiosity on the part of researchers in recent years.

The aim of this work is to show the utility of the use of a wind energy conversion system (WECS) driven by matrix converter compared to WECS fed by back-to-back converter.

## 2. WIND TURBINE SYSTEM MODELING

### A. Turbine Modeling

The theoretical power produced by the wind is given by [20-22]:

$$P_{tur} = C_p \cdot \frac{\rho \cdot S \cdot V^3}{2} \quad (1)$$

Where  $C_p$  denotes power coefficient of wind turbine, its evolution depends on the blade pitch angle ( $\beta$ ) and the tip-speed ratio ( $\lambda$ ) which is defined as [23]:

$$\lambda = \frac{R \cdot \Omega_{tur}}{V} \quad (2)$$

From summaries achieved on a wind of 1.5 MW, the expression of the power coefficient for this type of turbine can be approximated by the following equation [24, 25]:

$$C_p = \left(0.45 - (0.0167(\beta - 2))\right) \left(\sin\left(\frac{\pi(\lambda + 0.1)}{(15.5 - (0.3(\beta - 2)))}\right)\right) - (0.00184(\lambda - 3)(\beta - 2)) \quad (3)$$

Fig. 1 show the variation of the power coefficient ( $C_p$ ) versus the tip-speed ratio ( $\lambda$ ) for the pitch angle  $\beta = 2^\circ$ .

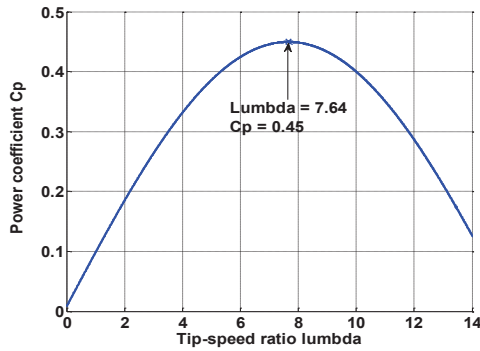


Fig. 1. Power coefficient versus tip speed ratio and pitch angle

This figure indicates that there is one specific point ( $\lambda_{opt}, C_{popt}$ ) at which the turbine is most efficient for  $\beta=2^\circ$ .

The aerodynamic torque expression is given by [23]:

$$T_{tur} = \frac{P_{tur}}{\Omega_{tur}} = C_p \cdot \frac{\rho \cdot S \cdot V^3}{2} \cdot \frac{1}{\Omega_{tur}} \quad (4)$$

The gearbox is installed between the turbine and the generator to adapt the turbine speed to that of the generator:

$$\Omega_{mec} = G \cdot \Omega_{tur} \quad (5)$$

The friction, elasticity and energy losses in the gearbox are neglected.

$$G = \frac{T_{tur}}{T_{mec}} \quad (6)$$

The mechanical equations of the system can be characterized by:

$$J \frac{d\Omega_{mec}}{dt} = T_{mec} - T_{em} - f\Omega_{mec} \quad (7)$$

With,  $J = \frac{J_{tur}}{G^2} + J_{gen}$

### B. Modeling of the DFIG with stator field orientation

The Park model of DFIG is given by the equations below [25-28]:

$$\begin{cases} V_{sd} = R_s i_{sd} + \frac{d\varphi_{sd}}{dt} - \omega_s \varphi_{sq} \\ V_{sq} = R_s i_{sq} + \frac{d\varphi_{sq}}{dt} + \omega_s \varphi_{sd} \end{cases} \quad (8)$$

$$\begin{cases} V_{rd} = R_r i_{rd} + \frac{d\varphi_{rd}}{dt} - \omega_r \varphi_{rq} \\ V_{rq} = R_r i_{rq} + \frac{d\varphi_{rq}}{dt} + \omega_r \varphi_{rd} \end{cases} \quad (9)$$

As the d and q axis are magnetically decoupled, the stator and rotor flux are given as:

$$\begin{cases} \varphi_{sd} = L_s i_{sd} + L_m i_{rd} \\ \varphi_{sq} = L_s i_{sq} + L_m i_{rq} \end{cases} \quad (10)$$

$$\begin{cases} \varphi_{rd} = L_r i_{rd} + L_m i_{sd} \\ \varphi_{rq} = L_r i_{rq} + L_m i_{sq} \end{cases} \quad (11)$$

With:  $L_s = L_{fs} + L_m$

$$L_r = L_{fr} + M^2 L_m$$

The active and reactive powers are defined as:

$$\begin{cases} P_s = V_{sd} i_{sd} + V_{sq} i_{sq} \\ Q_s = V_{sq} i_{sd} - V_{sd} i_{sq} \end{cases} \quad (12)$$

$$\begin{cases} P_r = V_{rd} i_{rd} + V_{rq} i_{rq} \\ Q_r = V_{rq} i_{rd} - V_{rd} i_{rq} \end{cases} \quad (13)$$

The DFIG model is presented in synchronous dq reference frame where the d-axis is aligned with the stator flux linkage vector  $\varphi_s$ , and then, ( $\varphi_{sq} = 0$ ,  $\varphi_{sd} = \varphi_s$ ) [13, 19]. In addition, considering that the resistance of the stator winding ( $R_s$ ) is neglected and the grid is supposed stable with voltage  $v_s$  and synchronous angular frequency ( $\omega_s$ ) constant what implies  $\varphi_{sd} = cst$ , the voltage and the flux equations of the stator windings can be simplified in steady state as [26-30]:

$$\begin{cases} V_{sd} = \frac{d\varphi_{sd}}{dt} = 0 \\ V_{sq} = \omega_s \cdot \varphi_{sd} = V_s \end{cases} \quad (14)$$

Hence, the relationship between the stator and rotor currents can be written as follows:

$$\begin{cases} i_{sd} = \frac{\varphi_s}{L_s} - \frac{L_m}{L_s} i_{rd} \\ i_{sq} = -\frac{L_m}{L_s} i_{rq} \end{cases} \quad (15)$$

From the equations (11) and (15), we can write:

$$\begin{cases} \varphi_{rd} = \left(L_r - \frac{M^2}{L_s}\right) i_{rd} + \frac{M}{\omega_s L_s} V_s \\ \varphi_{rq} = \left(L_r - \frac{M^2}{L_s}\right) i_{rq} \end{cases} \quad (16)$$

The expression of the stator and rotor voltage is given by:

$$\begin{cases} V_{sd} = \frac{R_s}{L_s} \varphi_{sd} - \frac{R_s}{L_s} L_m i_{rd} \\ V_{sq} = -\frac{R_s}{L_s} L_m i_{rq} + \omega_s \varphi_{sd} \end{cases} \quad (17)$$

$$\begin{cases} V_{rd} = R_r i_{rd} + \sigma \cdot L_r \frac{di_{rd}}{dt} + e_{rd} \\ V_{rq} = R_r i_{rq} + \sigma \cdot L_r \frac{di_{rq}}{dt} + e_{rq} + e_\varphi \end{cases} \quad (18)$$

Where:

$$\begin{cases} e_{rd} = -\sigma \cdot L_r \cdot \omega_r \cdot i_{rq} \\ e_{rq} = \sigma \cdot L_r \cdot \omega_r \cdot i_{rd} \\ e_\varphi = \omega_r \cdot \frac{M}{L_s} \cdot \varphi_{sd} \\ \sigma = 1 - \left( \frac{M}{\sqrt{L_s L_r}} \right)^2 \end{cases} \quad (19)$$

Stator and rotor active and reactive powers are described as:

$$\begin{cases} P_s = -\frac{V_s \cdot M}{L_s} \cdot i_{rq} \\ Q_s = \frac{V_s^2}{L_s \omega_s} - \frac{M \cdot V_s}{L_s} \cdot i_{rd} \\ P_r = g \cdot \frac{V_s \cdot M}{L_s} \cdot i_{rq} \\ Q_r = g \cdot \frac{V_s \cdot M}{L_s} \cdot i_{rd} \end{cases} \quad (20)$$

The electromagnetic torque is as follows [25]:

$$T_{em} = -P \cdot \frac{M}{L_s} \cdot \varphi_{sd} \cdot i_{rq} \quad (21)$$

### C. Modeling of Matrix Converter

The matrix converter studied in this paper is  $9 \times 3$  bidirectional switch single pole power converter. It is used to convert nine AC phase input voltage into three AC phase output, with a control of magnitude and frequency current output. The three phase output voltages ( $V_a$ ,  $V_b$ ,  $V_c$ ) are represented in terms of input voltages ( $V_A$ ,  $V_B$ ,  $V_C$ ) as follows [31, 32]:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ba} & S_{Ca} \\ S_{Ab} & S_{Bb} & S_{Cb} \\ S_{Ac} & S_{Bc} & S_{Cc} \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \quad (22)$$

Where the transfer matrix of MC is defined by the switching function ( $S_{jk}$ ) as:

$$S_{jk} = \begin{cases} 1 \rightarrow S_{jk} \text{ closed} \\ 0 \rightarrow S_{jk} \text{ open} \end{cases}, j \in \{A, B, C\}, k \in \{a, b, c\} \quad (23)$$

The input currents ( $I_A$ ,  $I_B$ ,  $I_C$ ) can also be calculated in terms of output currents ( $I_a$ ,  $I_b$ ,  $I_c$ ) as:

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ab} & S_{Ac} \\ S_{Ba} & S_{Bb} & S_{Bc} \\ S_{Ca} & S_{Cb} & S_{Cc} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (24)$$

Knowing that the transfer matrix of calculating input currents is the transpose of the transfer matrix in equation (22). Calculation time of each output phase voltage  $t_{jk}$  is a fraction of the switching frequency period  $T_s$ .

$$t_{jk} = S_{jk} \cdot T_s \quad (25)$$

$$\text{With } \sum t_{ja} = \sum t_{jb} = \sum t_{jc} = T_s$$

To eliminate open circuit to the output terminals or short circuit between input terminals, the switching constraint is defined as follow:

$$\sum S_{ja} = \sum S_{jb} = \sum S_{jc} = 1 \quad (26)$$

The maximum ratio between output and the input voltage is 86,6% [17].

$$q = \sqrt{\frac{V_o^2}{V_i^2}} \quad \text{with : } 0 < q \leq 0.866 \quad (27)$$

Based on the equations (26) and (27) matrix transfer can be calculated by the following three equations:

$$S_{jk} = \frac{1}{3} + \frac{2}{3} \frac{V_j V_k}{V_{is}^2} + \frac{2}{9} \frac{q}{q_s} \sin(\omega_i t + \phi_j) \cdot \sin(3\omega_i t) \quad (28)$$

$$V_j = V_{is} \cos(\omega_i t + \phi_j) \quad (29)$$

$$V_k = q V_{is} \cos(\omega_0 t + \phi_k) - \frac{q}{6} V_{is} \cos(3\omega_0 t) + \frac{1}{4} \frac{q}{q_s} V_{is} \cos(3\omega_i t) \quad (30)$$

The simulink bloc diagram of MC developed in this work is showing in Fig.2.

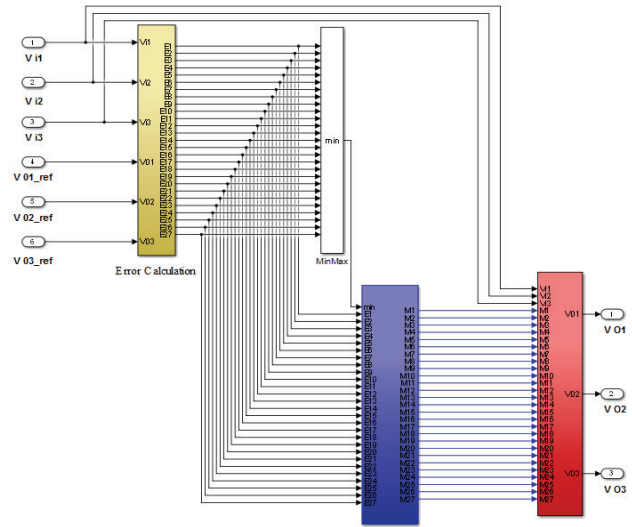


Fig. 2. Circuit diagram of MC

### 3. CONTROL STRATEGY

Preliminary work [12, 33] have shown the performance of the system using converters connected back-to-back by DC bus. However, this control structure despite its good performances, presents a certain inconvenience number and imperfection in the control. Especially, three step power conversion AC-DC-AC, complex structure and also high cost and important number of components. Based on these remarks, the interest of this paper is to propose another control configuration based on a matrix converter (MC). The studied system shown in Fig.3, is constituted of the turbine, the gearbox and the DFIG. The DFIG is connected directly to the grid via its stator but also via its rotor by means of MC. The modulation method (LMSE) is used to control the MC.

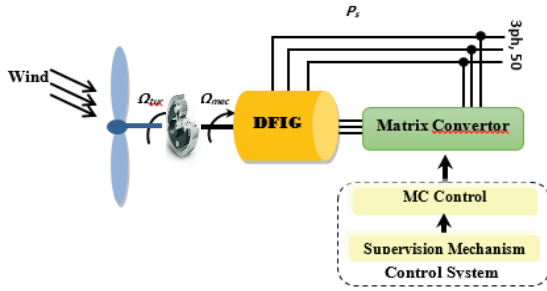


Fig. 3. Schematic diagram of DFIG wind turbine fed by MC

The operation of a wind turbine at variable speed is generally more beneficial over constant speed operation [5]. In this section two control loops are presented: control loop of the electric generator via the rotor side converter and control loop of the aeroturbine without speed control that provides the reference inputs of the first loop. The extraction of maximum power control is to adjust the torque of the DFIG to extract maximum power. In effect, the power extracted from the wind is maximized when the rotor speed is such that the power coefficient is optimal  $C_{popt}$ . Therefore, we must set the tip speed ratio on its optimal value  $\lambda_{opt}$ . The electromagnetic torque reference determined by MPP control power is thus expressed by the following equation [33-35]:

$$T_{em}^* = \frac{C_{popt} \cdot \rho \cdot \pi \cdot R^5}{2 \cdot G^3 \cdot \lambda_{opt}^3} \cdot \Omega_m^2 \quad (31)$$

Furthermore, equation (20) and (21) demonstrate that the electromagnetic torque and the stator reactive power can be controlled by means of the DFIG current  $i_{rq}$  and  $i_{rd}$  respectively. The model of DFIG in d-q reference frame with stator field orientation shows that the rotor currents can be controlled independently. The reference rotor currents  $i_{rd\_ref}$  and  $i_{rq\_ref}$  are given by:

$$\begin{cases} i_{rd\_ref} = \frac{\varphi_{sd}}{M} - \frac{L_s}{M \cdot V_{sq}} \cdot Q_{s\_ref} \\ i_{rq\_ref} = -\frac{L_s}{M \cdot P \cdot \varphi_{sd}} \cdot T_{em}^* \end{cases} \quad (32)$$

The proportional integral controller (PI) is widely used in the control of DFIG because of its simple structures and good performances. For the synthesis of the regulators we opted for the method of poles compensation ( $t_r = 0.005s$ ).

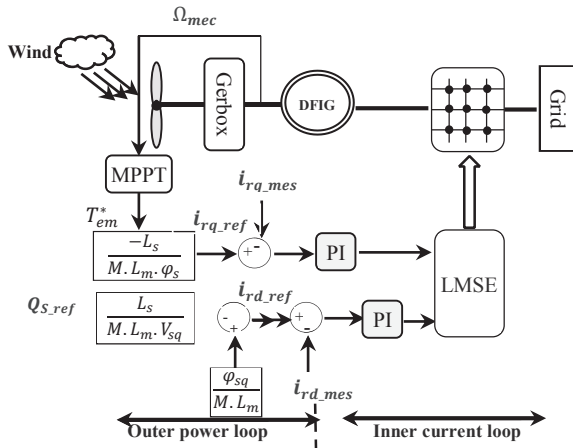


Fig. 4. Circuit diagram of WECS with MC

#### 4. SIMULATION RESULTS

In order to validate this comparative study, the two simulation programs: WCES driven by AC/DC /AC converter and WCES driven by matrix converter were tested for a variable wind profile expressed by the below relationship, and represented by figure 4.

$$V_w(t) = 8 + 0.2 * (\sin(0.1047 * t) + \sin(3.6645 * t)) + 2 * \sin(0.2665 * t)$$

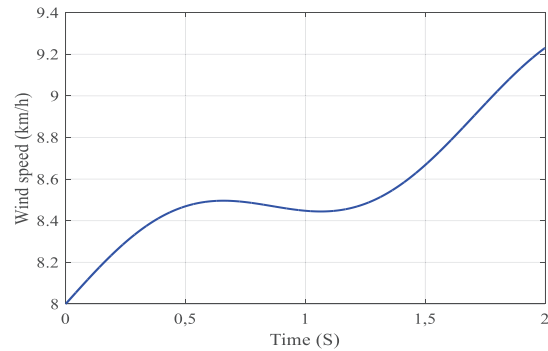


Fig. 4. Wind profile

Furthermore, a selected reactive power reference corresponding to the following algorithm (Table.2).

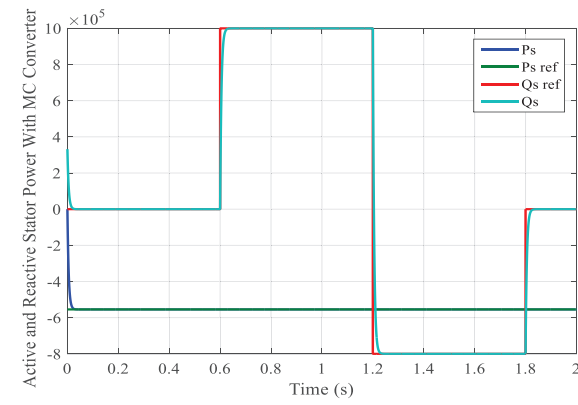
Figures 5\_a,b , 6\_a,b , 7\_a,b and 8\_a,b , shows, respectively, the forms of the active and reactive powers as well as their references obtained for the control configurations: WCES driven by AC/DC /AC converter and WCES driven by MC, For a final simulation time of 2 seconds and under the conditions cited above.

The active and reactive powers follow, correctly, their respective references. On the other hand, there is a perfect decoupling between the two power components. Indeed, despite the change in the references of reactive powers and consequently of their corresponding magnitudes, the active power keep a value corresponding to the maximum of the developed power.

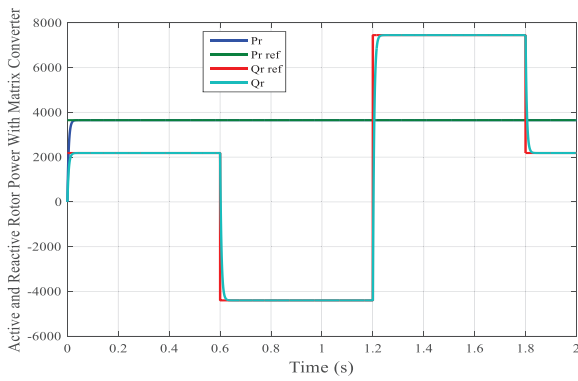
However, due to the use of AC / DC / AC double conversion, there are oscillations and deviations in power responses (See the zooms). It is also noted that the performance in terms of reference tracking and less than the results obtained with the configuration using the matrix converter.

Table 2. Operation Statuses of the Simulated DFIG

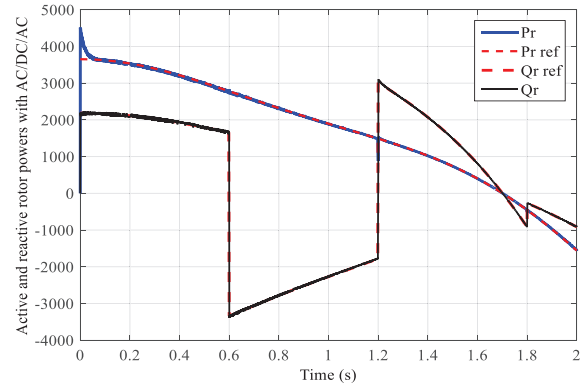
Status	Time (sec)	Reactive power (MVar)
1	$0 \leq t \leq 0.6$	0
2	$0.6 < t \leq 1.2$	1
3	$1.2 < t \leq 1.8$	-0.8
4	$1.8 < t \leq 2$	0



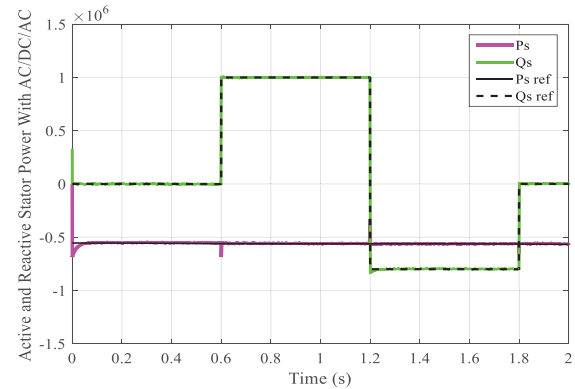
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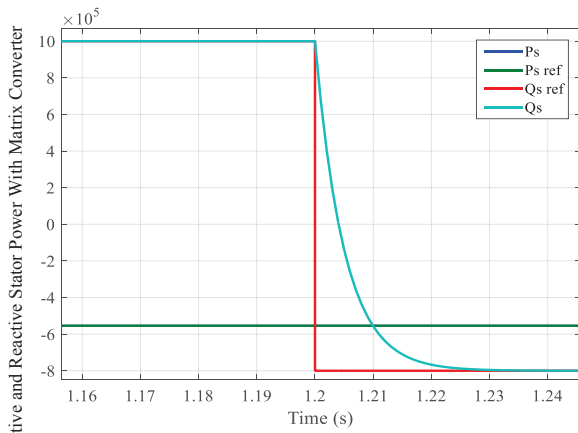
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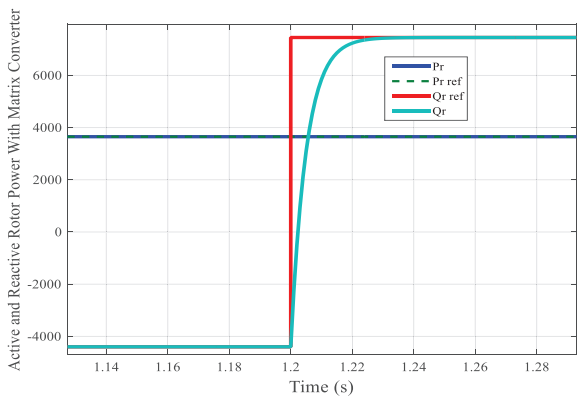
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Fig.5. Active and reactive powers responses with MC converter

Fig.7. Active and reactive powers responses with AC/DC/AC converter

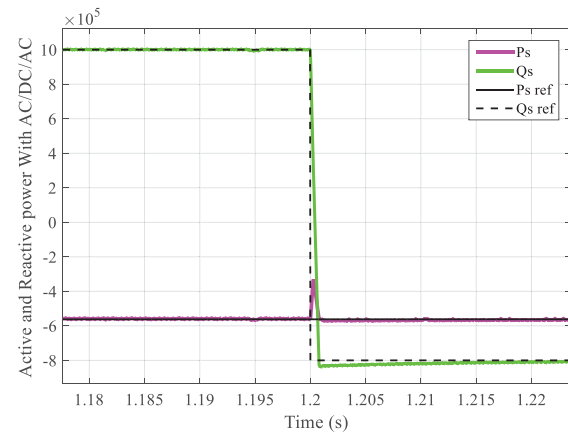


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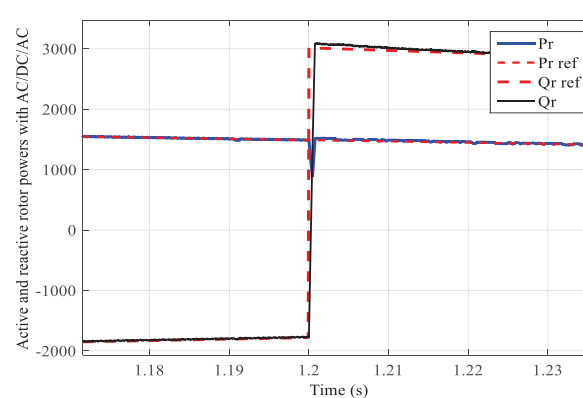


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Fig.6. Zoom active and reactive powers responses with MC converter



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Fig.8. Zoom active and reactive powers responses with AC/DC/AC



## 5. CONCLUSION

At the end of this study, the performance of the two variable speed wind energy conversion system based on the doubly fed induction generator driven by AC/DC/AC and WECS driven by matrix converter were simulated, analyzed and discussed. First, a modeling and a control strategy of DFIG based wind turbine are exposed. After, The MC-based structure proved to be more efficient compared to the AC / DC / AC structure. This, concerning of pursuing the set points of powers and mainly during the permanent regimes which are reached without recording oscillations on the responses. Also, a good stabilization of the active powers is noted even if the reactive power varies. The simulation results using software Matlab/Simulink show that the use of MC has given us good rotor currents and power waveforms and can operate with a unit power factor.

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