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COMPARATIVE STUDY OF TWO CONTROL SCHEMES FOR MAXIMUM POWER POINT TRACKING STRATEGY OF A WIND SYSTEM

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Key words: Maximum power point tracking, Wind turbine, Doubly fed induction generator, Grid side and rotor side converters, Speed and reactive power tracking, Active and reactive power control, Comparative study.

In this work, the maximum power point tracking (MPPT) of a wind system is achieved using two control schemes, either a decoupled control of speed and reactive power ((Ω-*Q*) control scheme) or an independently control of active and reactive power ((*P*-*Q*) control scheme). Indeed, the principal objective is the comparison of the two kinds of control schemes in terms of efficiency, costs, sizes, reliability and cumbersome. The control strategies are applied to the RSC of a wind energy conversion system (WECS) equipped by a DFIG. In addition, in the case of the (*P*-*Q*) control scheme, for the determination of the optimum stator active power reference in the MPPT mode, it is proposed to use the energetic balance sheet based on the rotor dynamic equation of the WECS. Elsewhere, the GSC is controlled to ensure a smooth dc bus voltage. The obtained MPPT results have been presented, discussed, and compared. Practically, the same results have been obtained. However, from a technical-economic point of view, it is shown that the (*P*-*Q*) control scheme is more reliable, cheaper, and less cumbersome comparatively to the (Ω-*Q*) control scheme.

1. INTRODUCTION

To limit the pollution problems around the planet, many efforts have been concentrated on the development of environmentally friendly sources of energies such as: wind and solar. The wind energy conversion system (WECS) conducted by a variable speed turbine have brought much attention for their ability of varying the generator active power or speed to accomplish the maximum power point tracking (MPPT) for variable wind speed profiles. Recently, wind turbine systems equipped by doubly fed induction generator (DFIG) have received increasing attention due to its remarkable advantages over other wind turbine generators.

Today, the MPPT operating mode is an important necessity in any renewable energy system such as: wind and solar [1]. In fact, the MPPT operation allows to system many important advantages including maximum power extraction, smoothness of the produced power and less mechanical stresses [2,3].

Every year, many original MPPT control strategies appear in various journals. Usually, in wind system the MPPT operation mode is accomplished either with the measurement of the wind speed and the generator rotational speed [3–10] or without any mechanical sensors [11–15]. Also, MPPT can be achieved by using either the decoupled control of speed and reactive power ((Ω-Q) control scheme) or the decoupled control of active and reactive power ((P-Q) control scheme). In the first category, a rotor speed controller is used. In this case, the active power is indirectly controlled to track its optimum value, but in the second ones, the active power is directly controlled by using an appropriate controller. In this case, the speed is indirectly controlled to track its optimum value.

Generally, for the first category, the optimum MPPT generator speed is calculated from the wind speed (measured or estimated). Traditionally, the second category needs predefined look up tables which summarizes the optimum MPPT electromagnetic torque or the MPPT active power.

In this paper the MPPT, in the case of the (*P-Q* control scheme), is achieved without the need to any predefined look up table. In fact, for determining the optimum stator active power reference for the MPPT operating mode, it is proposed to use the energetic balance sheet based on the rotor dynamic equation of the WECS. In literature, till now any study has introduced the (*P-Q* control scheme) based on the use of the energetic balance sheet based on the rotor dynamic equation of the WECS and any comparative study has been done between the two schemes.

The main purpose of this paper is to compare, from technical and economic point of view, between the two cited control schemes. In fact, the simulation results of the WECS operating in the MPPT using the ((Ω-*Q*) control scheme) and the ((*P-Q*) control scheme) are compared in terms of efficiency, reliability, costs, sizes and cumbersome.

2. MODELING OF THE WIND SYSTEM

The studied WECS is presented in Fig. 1.

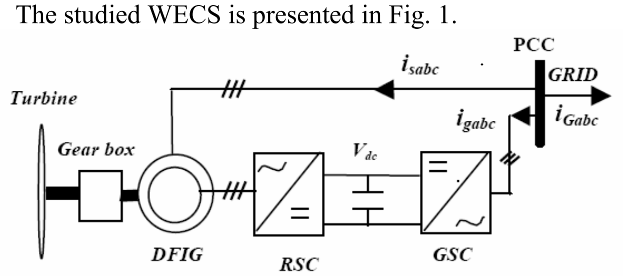

Fig. 1 – Layout of the WECS.

2.1. TURBINE MODELLING

The aerodynamic power extracted by the turbine from the wind has the following nonlinear equation:

$$p_{aer} = \frac{1}{2}\rho c_p(\lambda,\beta) s v^3, \quad (1)$$

with ρ: the air density; *s:* the swept surface (m²); *v:* the wind speed (m/s); c_p (λ, β): the turbine power coefficient; λ: the tip speed ratio and β: the blade pitch angle. The tip speed ratio is expressed by:

$$\lambda = \frac{R\omega_t}{v}, \quad (2)$$

where ω_t is the turbine speed (rad/s), and *R* is the blade radius (m).

Figure 2 illustrates the power coefficient as a function of λ, for a fixed pitch angle (β). So, to capture the maximum

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power from the wind, the turbine speed (ω_t) may be tracked to change according to the wind speed (v) variation to keep (λ) at the optimal value (λ_{opt}) (see Fig. 2). In this way the turbine can effectively extract the optimum power value from the wind.

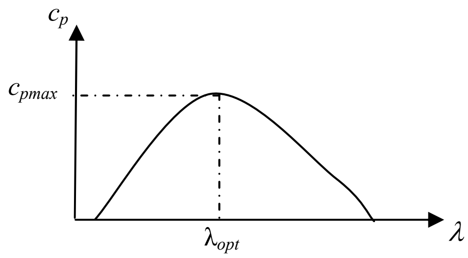

Fig. 2 – Power coefficient as a function of tip speed ratio.

2.1. MODELLING OF THE DFIG AND FIELD-ORIENTED CONTROL

In Park reference frame, the DFIG voltage and flux equations, are expressed by the following classical expressions [16,17]:

$$
\begin{aligned}
u_{ds} &= R_s i_{ds} + \frac{\mathrm{d}\Psi_{ds}}{\mathrm{d}t} - \omega_s \Psi_{qs},\\
u_{qs} &= R_s i_{qs} + \frac{\mathrm{d}\Psi_{qs}}{\mathrm{d}t} + \omega_s \Psi_{ds},\\
u_{dr} &= R_r i_{dr} + \frac{\mathrm{d}\Psi_{dr}}{\mathrm{d}t} - (\omega_s - \omega_r)\Psi_{qr},\\
u_{qr} &= R_r i_{qr} + \frac{\mathrm{d}\Psi_{qr}}{\mathrm{d}t} + (\omega_s - \omega_r)\Psi_{dr},
\end{aligned} \tag{3}
$$

$$
\begin{aligned}
\Psi_{ds} &= L_s i_{ds} + M i_{dr},\\
\Psi_{qs} &= L_s i_{qs} + M i_{qr},\\
\Psi_{dr} &= L_r i_{dr} + M i_{ds},\\
\Psi_{qr} &= L_r i_{qr} + M i_{qs}.
\end{aligned} \tag{4}
$$

The electromagnetic torque of the DFIG is expressed by:

$$T_{em} = \frac{3}{2} p \frac{M}{L_s}\left(i_{dr}\Psi_{qs} - i_{qr}\Psi_{ds}\right). \tag{5}$$

Elsewhere, at the generator side, the WECS mechanical equation is:

$$T_{em} = J\frac{\mathrm{d}\Omega_g}{\mathrm{d}t} + f\,\Omega_g + T_L. \tag{6}$$

The different WECS parameters are given in appendix. Ω_g, p are respectively the generator speed and its number of pole pairs. Elsewhere, in this study the total stator flux ψ_s is oriented with the d axis and supposed constant (it is the case stable grid) [18,19]. Then, the stator flux components are written as: $\psi_{ds} = \psi_s$ and $\psi_{qs} = 0$. Therefore, equations (3), (4) and (5) become respectively:

$$u_{ds} \approx 0, \tag{7}$$

$$u_s = u_{qs} \approx \omega_s \Psi_s, \tag{8}$$

$$\Psi_s = L_s i_{ds} + M i_{dr}, \tag{9}$$

$$0 = L_s i_{qs} + M i_{qr}, \tag{10}$$

$$T_{em} = -\frac{3}{2} p \frac{M}{L_s} \Psi_s i_{qr}, \tag{11}$$

where, u_s is the stator voltage magnitude. Furthermore, the instantaneous stator active and reactive power are [17–20]:

$$P_s = \frac{3}{2}\left(u_{ds} i_{ds} + u_{qs} i_{qs}\right), \tag{12}$$

$$Q_s = \frac{3}{2}\left(u_{qs} i_{ds} - u_{ds} i_{qs}\right). \tag{13}$$

By the use of equations (7)-(10), (12) and (13) are easily rewritten as:

$$P_s = -\frac{3u_s M}{2L_s} i_{qr}, \tag{14}$$

$$Q_s = \frac{3}{2}\frac{u_s}{L_s\omega_s}\left(u_s - M\omega_s i_{dr}\right). \tag{15}$$

3. **ROTOR SIDE CONVERTER CONTROL**

The goal of this section is to develop and inspect a control strategy of the RSC to realize the MPPT using two different control schemes that are detailed hereafter:

3.1. (Ω-*Q*) CONTROL SCHEME

From equation (11), the electromagnetic torque can be controlled to track its optimum value (T_{emref}) by modifying the rotor current component (i_{qr}) as follows:

$$i_{qrref} = -\frac{2L_s\omega_s}{3pu_s M} T_{emref}. \tag{16}$$

In addition, from equation (15), one can observe that the stator reactive power (Q_s) can be controlled by adjusting the other rotor current component (i_{dr}) as expressed by eq. (17).

$$i_{drref} = \frac{2L_s}{3u_s M}\left(\frac{3u_s^{\,2}}{2L_s\omega_s} - Q_{sref}\right). \tag{17}$$

Elsewhere, to achieve the MPPT, a speed fuzzy logic controller (FLC1) has been considered in this work (see Fig. 3). The MPPT generator speed reference is calculated by [20]:

$$\Omega_{gref} = \delta\frac{\lambda_{opt}}{R} v, \tag{18}$$

where δ is the WECS gear box.

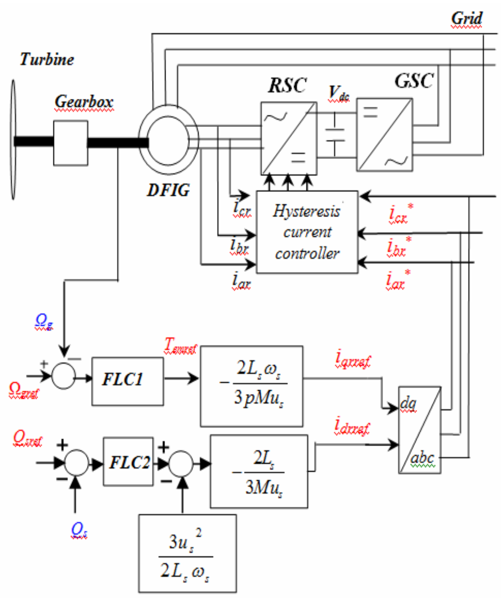

Fig. 3 – (Ω-*Q*) control scheme of the WECS.

Indeed, the generator speed (Ω_g) follows its optimum reference value (Ω_{gref}), by changing the rotor current component (i_{qr}) through the FLC1 (see Fig. 3). Also, the stator reactive power (Q_s) control is realized by using another FLC2, as shown in Fig. 3. Noting that, the similar inference table is used for the FLC1 and FLC2.

3.2. (*P-Q*) CONTROL SCHEME

Equation (14) shows that the stator active power (P_s) can be controlled to track its reference value (P_{sref}) by adjusting the rotor current component (i_{qr}) according to the following:

$$i_{qrref} = -\frac{2L_s}{3M\,u_s}P_{sref}\,. \tag{19}$$

Another fuzzy logic controller (FLC_3) has also been dedicated to control the stator active and reactive power to follow their references values according to the *P-Q* control scheme presented in Fig. 4.

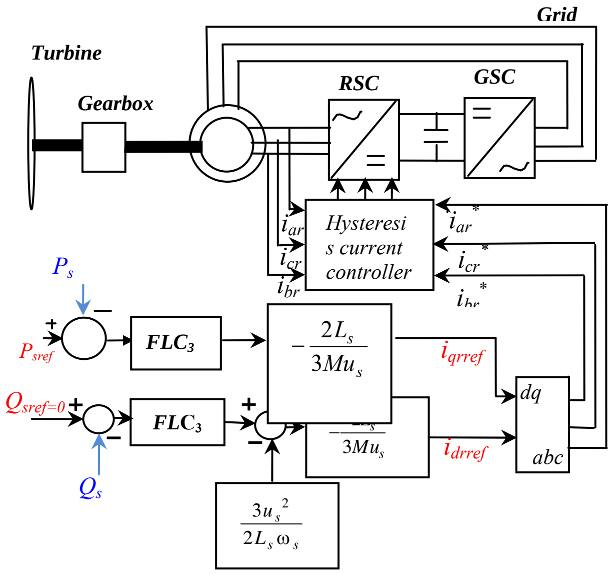

Fig. 4 – *P-Q* control scheme of the WECS.

In the aim to use the (*P-Q*) control scheme for achieving the MPPT strategy, it is necessary to determine the expression of the optimum stator active power reference (P_{sref}) (see Fig. 4).

As has been indicated in the abstract, a new expression for (P_{sref}) calculation is proposed in this work, indeed, P_{sref} calculation is based on the use of the energetic balance sheet equation of the WECS.

The combination of eq. (11) and eq. (14) permits to obtain the electromagnetic power of the DFIG as follows:

$$T_{em}\,\Omega_g = P_s(1-g), \tag{20}$$

where g is the DFIG slip range.

In the MPPT operating mode and based on the WECS mechanical (eq. (6)), eq. (20) can be rewritten as:

$$\begin{aligned} &P_{sref}(1-g_{ref}) = \\ &= J\frac{\Omega_{gref}(kT)-\Omega_{gref}((k-1)T)}{T}\Omega_{gref}(kT) + \\ &+ f\,\Omega_{gref}^{\,2}(kT) + P_{aerM}\ , \end{aligned} \tag{21}$$

where T is the sampling time; P_{aerM} is the maximum mechanical power that can be produced by the turbine that is calculated, for each value of wind speed (v), by using eq. (1):

$$P_{aerM} = \frac{1}{2}\rho\, c_{p\max}\, s\, v^3, \tag{22}$$

where c_{pmax} is the optimal value of the power coefficient (see Fig. 2). Elsewhere, g_{ref} is the slip range reference value of the DFIG in the MPPT mode that is calculated by the following equation:

$$g_{ref} = \frac{\omega_s - p\Omega_{gref}}{\omega_s}. \tag{23}$$

Finally, for the MPPT operating mode, the optimum stator active power reference (P_{sref}). is easily calculated from equation (21) as follows:

$$P_{sref} = \frac{J\frac{\Omega_{gref}(kT)-\Omega_{gref}((k-1)T)}{T}\Omega_{gref}(kT)+f\,\Omega_{gref}^{\,2}(kT)+P_{aerM}}{1-g_{ref}}. \tag{24}$$

4. SIMULATION RESULTS

In this section and for the two kinds of control schemes, the simulation results for a WECS of 10 kW equipped by a 7.5 kW DFIG and operated in the MPPT mode are presented, discussed and compared.

4.1. CASE OF THE Ω-*Q* CONTROL SCHEME

In this subsection, we are interested to control the WECS by using the Ω-*Q* control scheme (Fig. 3) to ensure the MPPT with a unity power factor at the stator side.

To test the control strategy and evaluate its performances, a filtered random wind speed, with an average value of 9 m/s, is applied to the WECS (see Fig. 5a). Figure 5 illustrates the obtained simulation results. From the different WECS responses, one can observe that the generator speed (Ω_g) tracks its optimum (Ω_{gref}) value according to the MPPT strategy (see Fig. 5b). Consequently, the power coefficient oscillates practically around its optimum value of: C_{pmax} = = 0.4993, as shown by Fig. 5c.

Figure 5d–e shows that the turbine aerodynamic power (P_{aer}) and the stator active power (P_s) are indirectly controlled to follow their optimum values (P_{aerM}, P_{sMPPT}) according the MPPT strategy. Also, and as can be seen from Fig. 5e, the stator reactive power (Q_s) is practically nil and then a unity power factor at the stator side is achieved. Finally, the stator phase current (Fig. 5f), varies according to the maximum stator active power (P_s) variation and proves that the maximum wind power is extracted and injected in the grid through the stator.

4.2. CASE OF THE *P-Q* CONTROL SCHEME

In this subsection, we are interested to control the WECS by using the *P-Q* control scheme (Fig. 4) to operate in the MPPT mode with a unity power factor at the stator side. Since the main objective is to compare the performances of the two control schemes (Ω-*Q* and *P-Q*), we have applied to the WECS the same wind speed profile as in Section 4.1. Figure 6 illustrates the simulation results.

From the different WECS responses (Fig. 6), one can observe that the same results have been practically obtained comparatively to those shown in Fig. 5. In fact, from Fig. 6b one can remark that the generator speed (Ω_g) is indirectly controlled to follows its optimum value as shown by Fig. 6b as in Fig. 5b. As a result, the power coefficient oscillates around its optimum (see Fig. 6c), as in Fig. 5d. The turbine aerodynamic power (P_{aer}) follows also its optimum value

(P_{aerM}) (see Fig. 6d). As in Fig. 5e, Fig. 6e shows that the stator active and reactive power are directly controlled through the FLC3 to follow their references values to guarantee the maximum power production with a unity power factor at the stator side. Finally, as in Fig. 5f, the stator phase current (Fig. 6f) varies also according to stator active power variation and proves that the maximum power is extracted from the wind and injected in the grid through the stator.

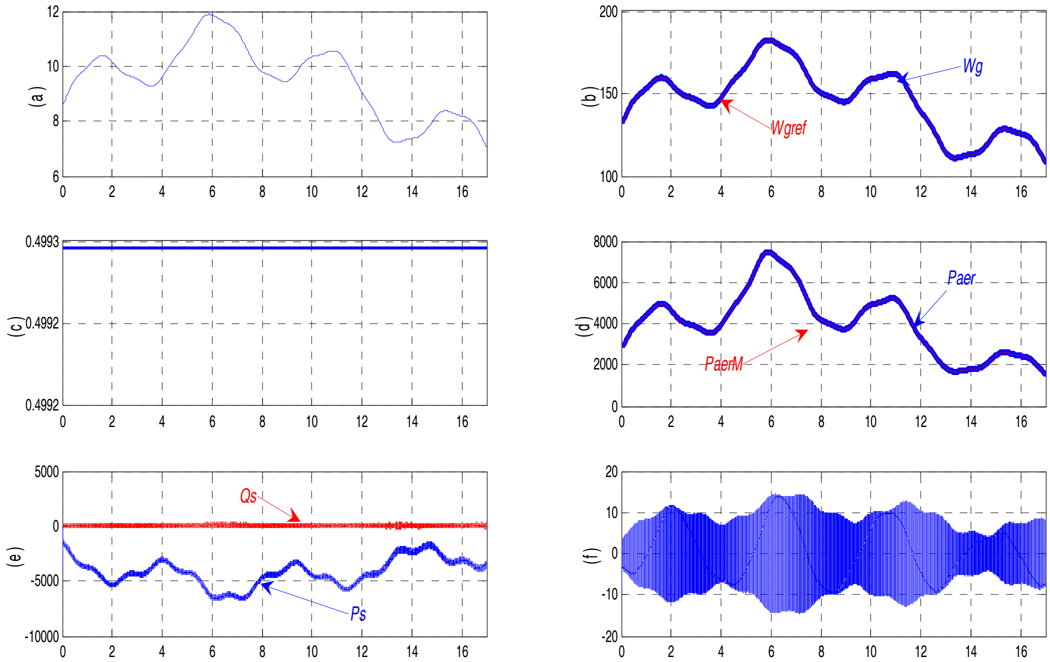

Fig. 5 – MPPT results using (Ω-Q control scheme): a) wind speed (v) [m/s]; b) generator speed (Ω_g) and its MPPT reference (Ω_{gref}) [rad/s]; c) power coefficient (C_p); d) aerodynamic power (P_{air}) and its optimal reference value (P_{airM}) [W]; e) stator active power (P_s) [W] and stator reactive power (Q_s) [var]; f) stator phase current (i_{as}) [A].

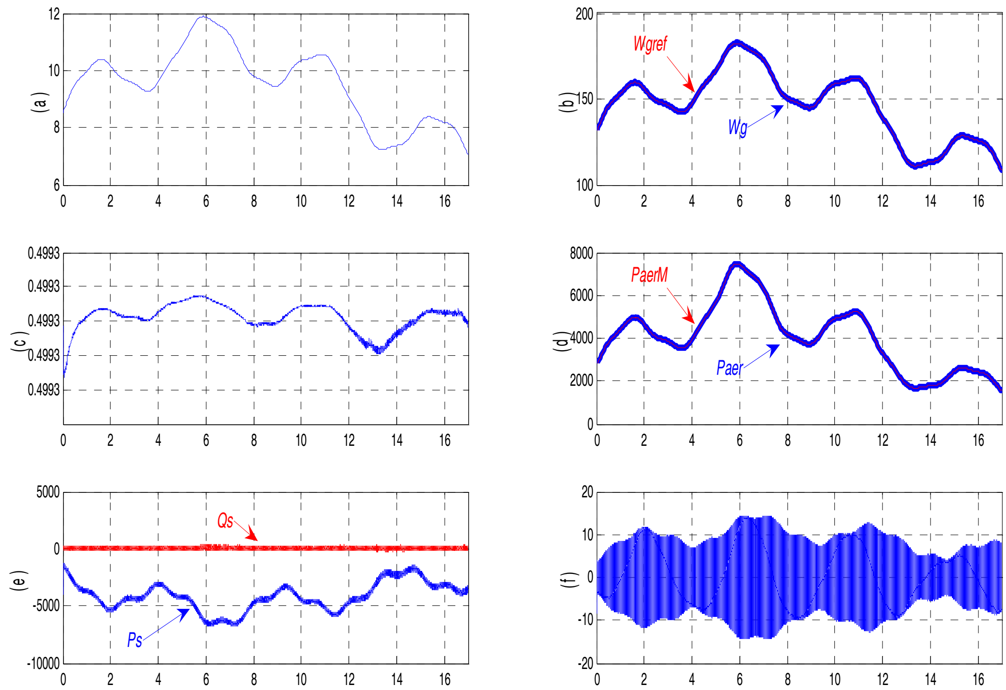

Fig. 6 – MPPT results using (P-Q control scheme): a) wind speed (v) [m/s]; b) generator speed (Ω_g) and its MPPT reference (Ω_{gref}) [rad/s]; c) power coefficient (C_p); d) aerodynamic power (P_{air}) and its optimal reference value (P_{airM}) [W]; e) stator active power (P_s)[W] and stator reactive power (Q_s) [var]; f) stator phase current (i_{as}) [A].

Hence, theoretically, to control the WECS for operating in the MPPT mode for a wide range of the wind speed, one can use either the Ω-Q or the P-Q control scheme. However, technically, the P-Q control scheme is more reliable and cheaper than the Ω-Q control scheme, because it does not require any generator speed sensor (or observer) which is the main disadvantage of the Ω-Q control scheme. In fact, the generator speed sensor makes the system less reliable, and the implementation of the speed generator observer is very complicate. In addition, two other electrical sensors are needed for the stator voltage and current measurement which are indispensable for the instantaneous stator reactive power calculation. On the other hand, the P-Q control scheme can be implemented with using only the two last electrical sensors (stator voltage and current measurement) for the instantaneous stator active (P_s) and reactive (Q_s) power calculation.

5. CONCLUSIONS

The work, presented in this paper, concerns a comparative study between two kinds of control schemes ((Ω-Q) and (P-Q) control strategies) for a WECS operated in the MPPT mode. The performances of the two kinds of control schemes are compared in terms of efficiency, costs, sizes, reliability and cumbersome. Theoretically and by simulation, the use of the two control schemes gives practically the same results. But technically, the use of the speed sensor (or observer) increases considerably the cost, hardware complexity and reduces the reliability of the system in the case of the Ω-Q control scheme. But, for the second control scheme, the stator active and reactive power calculation needs only two simple electrical sensors for stator voltage and current measurement. In addition, the reference optimum active power (P_{sref}) is calculated by resolving the electromagnetic power equation of the generator (equation 21) written in the MPPT mode. This later is a function of the WECS mechnical parameters and characteristics (J, f and C_p (λ, β) curve) equation (24) which must be accuracy identified. Also, it is important to note that the reference stator active power (P_{sref}) in the MPPT is determined without the need to any predefined look up table summarizing the optimum MPPT electromagnetic torque or the MPPT active power for all wind speed values.

Finally, through this study, it has been shown that the use of the Ω-Q or the P-Q control schemes leads to the same results practically. But due to the complicated mechanical (or observer) speed sensor, one can conclude that the P-Q control scheme is more reliable than the Ω-Q control scheme in terms of costs and hardware complexity. As perspectives, this study can be extended for any wind system based on other generators kinds.

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APPENDIX

Turbine parameters	Value
Power [kW]	10
Blades number	3
Turbine radius [m]	3
WECS gear box ration	8
DFIG Parameters	
Power [kW]	7.5
Stator phase resistance R_s [Ω]	0.455
Rotor phase resistance R_r [Ω]	0.62
Stator phase inductance L_s [H]	0.084
Rotor phase inductance L_s [H]	0.081
Magnetizing inductance M [H]	0.078
System inertia [kg·m^2]	0.3125
Friction factor [N·m·s]	0.00673

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