A proposed strategy for power optimization of a wind energy conversion system connected to the grid

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A B S T R A C T

Many strategies have been developed in last decade to optimize power extracted from wind energy conversion system where many of them can produce only 30% more than the rated power. With the considered strategy, the generated wind power can reach twice its nominal value using a fast and reliable fully rugged electrical control. Indeed, by employing a suitable control technique where the produced power in super-synchronous mode is derived from both the stator and the rotor. Also, the rotor provided power in this case grows up 100% comparing to stator rated power. However, this solution permits to maintain the wind energy conversion system operation in its stable area.

The considered system consists of a doubly fed induction generator whose stator is connected directly to the grid and its rotor is supplied by matrix converter. In this paper, the sliding mode approach to achieve active and reactive power control is used. This latter is combined with de Perturbation and Observation Maximum Power Point Tracking used in the second operation zone. The obtained simulations results are assessed and carried out using Matlab/Simulink package and show the performance and the effectiveness of the proposed control.

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1. Introduction

Due to its advantages, wind energy attracts many researchers in the last decade. Some authors focused their research on problems relating to the storage of this energy like John and David who led a study on probabilistic energy storage and its use with intermittent renewable energy [1]. Xiaosong et al. made comparative study of three electrochemical energy buffers applied to a hybrid bus Powertrain with optimal sizing and energy management [2]. Others are more interested in improving the quality of energy produced and injected into the grid and working on models and various control techniques. In [3], the authors propose a model to control a wind turbine associated with a flywheel energy storage system to improve the quality of power injected into the grid. In [4], a grid power flux control of a variable speed wind generator which consists of a doubly fed induction generator is investigated. A new control strategy for small wind farm is proposed in [5] to improve supplying reactive power and transient stability. To avoid strong transients in the turbine components, a cascaded nonlinear controller is designed in [6] for a variable speed wind turbine equipped with a doubly fed induction generator. In [7], authors proposed a control method for a doubly fed induction generator used in wind energy conversion systems. Three different controllers are presented: proportional-integral, polynomial RST and linear quadratic Gaussian. As an alternative to conventional methods, a nonlinear predictive control approach is developed for a doubly fed induction generator in [8]. In [9], authors presented the design and the implementation of a model reference adaptive control. The active and reactive power regulation which is achieved below synchronous speed of a grid connected wind turbine based on a doubly fed induction generator is investigated. To reduce the total harmonic distortion and enhance power quality during disturbances, an unconventional power electronic interface for a wind energy conversion system is presented in [10]. Other researchers have exploited the advantages of matrix converters which are better adapted to the AC/AC conversion over the classic converter topologies as back to back converters. Indeed, in [11] a grid connected wind power generation scheme using a doubly fed induction generator with a direct AC/AC matrix converter is presented. To reduce large active and reactive power ripples which is one of the main drawbacks on conventional method, a new strategy is developed in [12] for a matrix converter-fed doubly fed induction generator. In [13], authors investigated a three-level sparse matrix converter associated to a grid connected variable speed wind generation scheme using a doubly fed induction generators.

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Other researchers are interested in the study of wind generators themselves to improve their performances. Indeed, several studies have used different control strategies in order to optimize the extracted power from variable speed wind turbine. In [14], an autonomous induction generator driven with a wide speed range turbines controlled by the strategy of saturation effect compensation is presented but the maximum speed using this strategy does not exceed 13% of the rated speed.

Unconventional converter is proposed in [15]. To improve the used conversion energy system, the proposed converter has been connected to the rotor of the doubly fed generator with a fraction equal to 30% of the total power. This explains that, the generator speed does not exceed 30% in the synchronism speed. A high dynamic control of a generator with the speed range up to 20% is developed in [16]. A nonlinear robust control system technique for converting wind energy is performed in [17]. However, once again, the speed does not exceed 30% of its nominal value. In all above cited research works, the rated power and speed have been dealt with improving the generated power quality, with out exceeding 30% of rotor rated power. Yong et al. conducted a very interesting work where they have operated a double stator induction machine to reach the speed up to twice the nominal value [18]. But the maximum power extracted using their system do not have been doubled since one of the generator stators is controlled by static excitation. A solution to double a rated power at a double speed, is proposed in [19]. However, the system is entirely grid interfaced, ie requiring two power converters. In this context, the present deals and focuses on improving the performances of a WECS based on DFIG, using one power converter, expanding the speed variation range and arriving to extract a power that can reach the twice the rated power. Obviously, this cannot be done without taking into account the electrical and mechanical constraints related to the wind turbine operation in the range of high speeds. For this, we proceed as follows: When the turbine torque is less than its nominal value the MPPT algorithm is applied. Otherwise, the MPPT strategy is stopped and limits the turbine torque at its nominal value. Several MPPT algorithms are proposed in the literature. The most used is that named Perturbation and Observation (P&O). It is to note that it was always used in the Zone-I. In our case, an extension to the Zone-II is performed to taking into account the above-cited electrical constraints. Consequently, the stator power is also fixed, leaving the turbine speed increase above its synchronous value and the rotor becomes a generator of electric power that increases and reaches its nominal value when the turbine speed is doubled. Thus, the power generated by the rotor is added to that of the stator that are injected to the grid. In terms of control techniques, the sliding mode control, which is a robust and reliable approach is suitable and gives an added value to WECS based on DFIG. In [20] one found the impact on the active and reactive powers values is important for PI controller where as it is almost non-existent for SMC controller. In [21] sliding mode control strategy is used for tracking power photovoltaic system. In [22], robustness is tested with the respect the uncertainties parameters. Thus, the SMC is chosen as a control technique for the studied system. The global system, represented in Fig. 1, is modeled and simulated under Matlab/Simulink and the obtained simulations results are presented to prove the validity of the proposed strategy.

2. Proposed system

The proposed system consists of (WECS) based on a DFIG of 1.5 MW supplied by a matrix converter and connected to the grid (Fig. 1). An optimization program, based on the Perturbation and Observation (P&O) method is used to determinate the optimal values of power and speed which will be used in the control of active and reactive power. This control is achieved using sliding mode controller (SMC). The matrix converter is dimensioned at 100% of rated power generator. The wind turbine is designed to operate in over rated speed.

3. Modeling of the global system

3.1. Wind generator modeling

3.1.1. Modeling of the wind turbine

The power available and recoverable from the turbine is expressed by the following relationship [23]:

\[ P_{\text{wind}} = \frac{1}{2} \rho \pi R^2 \left( \frac{v^2}{2} - C_{\text{p}} \frac{v^2}{2} \right) \]

where

- \( P_{\text{wind}} \) is the wind power,
- \( \rho \) is the air density,
- \( R \) is the turbine radius,
- \( v \) is the wind velocity,
- \( C_{\text{p}} \) is the power coefficient,
- \( \lambda \) is the tip speed ratio.

The wind turbine operates in the zone corresponding to the maximum capture power, the wind generator is controlled by a grid connected matrix converter and the stator circuit is controlled by a sliding mode controller (SMC). The turbine becomes a generator when the turbine speed increases above its synchronous value and the rotor becomes a generator of electric power that increases and reaches its nominal value when the turbine speed is doubled.
\[ P_{\text{wind}} = \frac{1}{2} \rho \cdot \pi \cdot R^2 \cdot v_{\text{wind}}^3 \]  
\[ \text{where } \rho \text{ is the air density, } R \text{ is the blade length and } v_{\text{wind}} \text{ the wind velocity.} \]

The turbine converts some of the recoverable power to an aerodynamic power on the rotating shaft which is given by \[24,25\]:

\[ P_{\text{mec}} = \frac{1}{2} \rho \cdot \pi \cdot R^2 C_p(\lambda, \beta) \cdot v_{\text{wind}}^3 \]  
\[ \text{where } C_p \text{ is the power coefficient of the turbine, } \lambda \text{ is tip speed ratio (TSR) and } \beta \text{ is the blade pitch angle.} \]

In this case, the blade pitch angle \( \beta \) is set zero, so the variation of the power coefficient \( C_p \) is considered as function of the tip speed ratio \( \lambda \) (Fig. 2).

The aerodynamic torque of the turbine is defined by the ratio of mechanical power to the rotational speed of the blades [25]:

\[ T_i = \frac{P_{\text{mec}}}{\Omega} \]  
\[ \text{Therefore, the mechanical torque from the gearbox applied to the generator shaft is connected to the aerodynamic torque with the following expression [25]:} \]

\[ T_g = T_i \frac{G}{\Omega} \]  

where \( G \) is gearbox.

3.1.2. DFIG modeling

The Park transformation applied for the electrical equations of the DFIG [26,36] where the reference is related to the rotating field allows us to achieve the following electrical system equations:

\[ \begin{align*}
  v_{sd} &= R_s i_{sd} + \frac{d}{dt} i_{sq} \\
  v_{sq} &= R_s i_{sq} + \frac{d}{dt} i_{sd} \\
  v_{rd} &= R_r i_{rd} + \frac{d}{dt} i_{rd} \\
  v_{rq} &= R_r i_{rq} + \frac{d}{dt} i_{rq}
\end{align*} \]  
\[ \text{The flux equations written in } d-q \text{ reference frame are:} \]

\[ \begin{align*}
  \phi_{ad} &= L_a i_{ad} + L_m i_{dq} \\
  \phi_{aq} &= L_a i_{aq} + L_m i_{dq} \\
  \phi_{rd} &= L_r i_{rd} + L_m i_{dq} \\
  \phi_{rq} &= L_r i_{rq} + L_m i_{dq}
\end{align*} \]  

The mechanical equation is given by:

\[ T_{em} = T_i + J \frac{d\Omega_{\text{mec}}}{dt} + f \Omega_{\text{mec}} \]  

The electromagnetic torque \( T_{em} \) can be written as follow:

\[ T_{em} = P_{\text{mec}} \left( \phi_{ad} i_{rd} - \phi_{rd} i_{aq} \right) \]  

The active and reactive power stator and rotor are expressed by:

\[ \begin{align*}
  P_s &= v_{sd} i_{sd} + v_{sq} i_{sq} \\
  Q_s &= v_{sd} i_{sq} - v_{sd} i_{sq} \\
  P_r &= v_{rd} i_{rd} + v_{rq} i_{rq} \\
  Q_r &= v_{rq} i_{rd} - v_{rq} i_{rq}
\end{align*} \]  

The stator and rotor angular velocities are linked by the following relation:

\[ \omega_s = \omega + \omega_r \]
where

\[ \omega_s: \text{Stator angular speed (rad/s).} \]
\[ \omega_r: \text{Rotor angular velocity (rad/s).} \]
\[ \omega: \text{Angular speed (rad/s).} \]

The active and reactive powers of the DFIG are expressed by:

\[
\begin{aligned}
P_g &= P_s + P_i \\
Q_g &= \frac{Q_s}{3} + Q_i
\end{aligned}
\tag{10}
\]

where

\[ Q_{st}: \text{Reactive power from the converter grid side.} \]
\[ Q_{si}: \text{Reactive power injected into the grid.} \]
\[ Q_i: \text{Reactive power of the stator.} \]

The matrix converter (MC) offers the possibility of controlling the input power factor [26–30]. This work, the grid is assumed stable. Therefore, to improve the efficiency of the wind power generator, the stator reactive power is maintained at zero value.

3.2. Matrix converters modeling

The MC is an AC/AC converter which converts input line voltage into variable voltage with unrestricted frequency without using an intermediate storage unit [27]. This is achieved by a matrix of nine power switches connecting each input phase \( (a, b, c) \) to each output phase \( (A, B, C) \). It is recommended to close only one switch in each group to avoid short-circuiting the source. Similarly, the converter often feeding an inductive load, the opening of all the switches in the same group causes high voltages that can damage the circuit [31]. The simplified three phases- three phases MC topology incorporated in system of wind generator is shown in Fig. 3. The matrix converter is modeled by its output voltages and input currents in terms of switching functions which are expressed by the following matrices:

\[
\begin{bmatrix}
\nu_a(t) \\
\nu_b(t) \\
\nu_c(t)
\end{bmatrix} =
\begin{bmatrix}
S_{aA}(t) & S_{aB}(t) & S_{aC}(t) \\
S_{bA}(t) & S_{bB}(t) & S_{bC}(t) \\
S_{cA}(t) & S_{cB}(t) & S_{cC}(t)
\end{bmatrix}
\begin{bmatrix}
\nu_a(t) \\
\nu_b(t) \\
\nu_c(t)
\end{bmatrix}
\tag{11}
\]

\[
\begin{bmatrix}
i_a(t) \\
i_b(t) \\
i_c(t)
\end{bmatrix} =
\begin{bmatrix}
S_{aA}(t) & S_{aB}(t) & S_{aC}(t) \\
S_{bA}(t) & S_{bB}(t) & S_{bC}(t) \\
S_{cA}(t) & S_{cB}(t) & S_{cC}(t)
\end{bmatrix}
\begin{bmatrix}
i_a(t) \\
i_b(t) \\
i_c(t)
\end{bmatrix}
\tag{12}
\]

General form of the switching pattern is shown in Fig. 4.

The connection function that describes the logic state of each switch [32] is:

\[ S_{ij}(t) = 1 \text{ if the switch } T_{ij} \text{ is closed.} \]
\[ S_{ij}(t) = 0 \text{ if the switch } T_{ij} \text{ is open.} \]

where \( i \in \{a, b, c\} \), \( j \in \{A, B, C\} \).

In order to avoid short-circuited input terminals and open-circuited output phases, these switching functions should satisfy the following constraint equation:

\[ S_{ai} + S_{bj} + S_{cj} = 1 \tag{13} \]

Several techniques are published for switching the MC. In our case, we have adopted for the indirect vector modulation which offers better performances [33,34].

Vector modulation for matrix converter describes a fictional equivalent circuit combining two stages, inverter and rectifier stage, which are linked by a fictional DC voltage \( V_{DC} \) (Fig. 5(a)).

The space vector rectifier current is seen Fig. 5(b). Fig. 5(c) shows the vectors that the output inverter can form by applying the DC-link voltage to the output terminals.

\[
\begin{aligned}
I'_i &= \frac{1}{2} (i_a + a i_b + a^2 i_c) \\
V'_a &= \frac{1}{2} (V_a + a V_b + a^2 V_c)
\end{aligned}
\tag{14}
\]

The position of the reference vectors, voltages and currents \( V'_a, I'_i \) respectively, in the space phasor, allows the switching sequences generation [35].
3.3. Control power of WECS

3.3.1. Determination of the turbine reference values

As already mentioned, in the region of stable operation, the optimal reference values of the power ($P_{\text{mec, opt}}$) have to be injected into the grid and the rotational speed of the turbine ($\omega_{\text{mec, opt}}$) on the input shaft will be determined by the optimization algorithm based on the Perturbation and Observation (P&O) method (Fig. 6).

Optimal power reference to inject in the grid is determined as follows:

$$P_{\text{grid, ref}} = -\eta \cdot P_{\text{mec, opt}}$$ (15)
Mechanical speed reference is maintained equal to the optimal mechanical speed
\[ \Omega_{\text{mec, ref}} = \Omega_{\text{mec, opt}} \] (16)

The rate power of the considered machine is 1.5 MW, the iron losses and mechanical losses are neglected, the DFIG efficiency is estimated to 95% and the converter losses are supposed neglected. The developed operating principle can be illustrated by Fig. 7.

3.3.2. Stator flux oriented control

By choosing a diphase reference frame \(d-q\) related to the stator spinning field pattern and aligning the stator vector flux with the axis \(d\), we can write [31]

\[
\begin{align*}
\varphi_{sd} &= \phi_d \\
\varphi_{sq} &= 0
\end{align*}
\] (17)

For high and medium wind power, the voltage drop across the stator resistance can be neglected, so we can obtain the stator voltages and fluxes as follows:

\[
\begin{align*}
\varphi_{ad} &= \phi_d = L_s i_d + L_m i_d; \quad \varphi_{aq} = L_s i_q + L_m i_q \\
\varphi_{rd} &= 0 = L_r i_q + L_m i_d; \quad \varphi_{rq} = L_r i_q + L_m i_q
\end{align*}
\] (18)

The torque expression Eq. (8) can be rewritten by the Eq. (19) which depends only on the component \(i_q\)

Fig. 6. Flowchart of the optimization algorithm.
The equivalent control vector and \( V_r \) is the correction factor calculated so that the stability conditions are satisfied. The selected Lyapunov function for the sliding mode control should be chosen to satisfy the Lyapunov stability criteria:

\[
V = \frac{1}{2} S(x)^2 \quad (25)
\]

This can be assured for:

\[
\dot{V} = S(x) \cdot \dot{S}(x) \quad (26)
\]

It is to note that is strictly positive. Principally, Eq. (25) states that the squared "distance" to the surface, measured by \( e(x)^2 \), decreases along all system trajectories. Therefore, Eqs. (26) and (27) satisfy the Lyapunov condition. The selected Lyapunov function guaranteeing the stability of the whole control system and has the following form:

\[
U = U_{eq} + U_e \quad (28)
\]

With \( U \) is the control vector, \( U_{eq} \) is the equivalent control vector and \( U_e \) is the correction factor calculated so that the stability conditions for the selected control are satisfied.

\[
U_e = k \cdot \text{sat}(S(x)) \quad (29)
\]

where \( \text{sat}(S(x)) \) is the saturation function and \( k \) is the controller gain.

The method in [37] is adopted for the switching surface function to ensure the convergence of the state variable \( x \) to its reference value \( x_{opt} \).
where $e$ is the tracking error vector, $\zeta$ is a positive coefficient and $n$ is the relative degree.

### 3.3.4. The DFIG control

The active and reactive power errors are respectively defined as:

$$
S(P) = PG_{\text{ref}} - PG
$$

$$
S(Q) = QG_{\text{ref}} + QG
$$

The first order derivative of Eq. (31), gives:

$$
\dot{S}(P) = \dot{PG}_{\text{ref}} - \dot{PG}
$$

$$
\dot{S}(Q) = \dot{QG}_{\text{ref}} + \dot{QG}
$$

Replacing the powers in Eq. (32) by their expressions given in Eq. (20), we obtained:
Replacing the currents in Eq. (33) by their expressions given in Eq. (22), we obtain:

\[
\begin{align*}
\dot{S}(P) &= \hat{P}_{\text{ref}} + V_i \frac{1}{L_p} (1 - s) i_q \\
\dot{S}(Q) &= \hat{Q}_{\text{ref}} + V_i \frac{1}{L_p} i_q
\end{align*}
\]

Replacing the voltages \( V_{\text{ref}} \) by \( V_{\text{ref}} + V_{\text{lq}} \), the Eq. (34) became:

\[
\begin{align*}
\dot{S}(P) &= \hat{P}_{\text{ref}} + V_i \frac{1}{L_p} (1 - s) \left( V_{r} - R_{Ld} i_d - s \omega_{L} L_{r} i_q - z \frac{1}{L_p} i_q \right) \\
\dot{S}(Q) &= \hat{Q}_{\text{ref}} + V_i \frac{1}{L_p} \left( V_{rd} - R_{Ld} i_d + s \omega_{L} L_{r} i_q \right)
\end{align*}
\]
During the sliding mode and in permanent mode we have:

\[ S(P) = 0; \quad S(Q) = 0 \]

We obtain equivalent control \( V_{\text{dipq}} \) by using Eq. (35):

\[
\begin{aligned}
S(P) &= \dot{P}_{\text{ref}} + V_{\text{dipq}} \frac{1}{L_m} (1 - S) \left( V_{\text{reqq}} + V_{\text{qnn}} - R_t i_{\text{eq}} - s \sigma_L i_{\text{id}} - s \frac{\lambda_n}{L_t} \right) \\
S(Q) &= \dot{Q}_{\text{ref}} + V_{\text{dipq}} \frac{1}{L_m} \left( V_{\text{reqq}} + V_{\text{qnn}} - R_t i_{\text{eq}} + s \sigma_L i_{\text{iq}} \right)
\end{aligned}
\]  

During the sliding mode and in permanent mode we have:

\[ S(P) = 0; \quad S(Q) = 0; \quad S(P) = 0; \quad S(Q) = 0; \quad V_{\text{ref}} = 0; \quad V_{\text{rnn}} = 0 \]

We obtain equivalent control \( V_{\text{dipq}} \) by using Eq. (35):

\[
\begin{aligned}
V_{\text{dipq}} &= -\dot{Q}_{\text{ref}} \frac{\alpha_L}{\alpha_m} + R_t i_{\text{eq}} - s \sigma_L L_t i_{\text{eq}} \\
V_{\text{dipq}} &= -\dot{P}_{\text{ref}} \frac{\alpha_L}{\alpha_m} \frac{1}{1 + s} + R_t i_{\text{eq}} + s \sigma_L L_t i_{\text{id}} + s \frac{\lambda_n}{L_t}
\end{aligned}
\]  

To obtain good performances, dynamic and commutations around the surfaces, the control vector applied as follows:

\[
\begin{aligned}
V_{\text{dipq}} &= V_{\text{dipq}} + V_{\text{ref}} + k_t \cdot \text{sat}(S(P)) \\
V_{\text{qnn}} &= V_{\text{qnn}} + V_{\text{rnn}} + k_q \cdot \text{sat}(S(Q))
\end{aligned}
\]  

The sliding mode will exist only if the following condition is verified:

\[ S \cdot S < 0 \]  

3.3.5. Control of the proposed system

The block diagram of SMC applied in our system is illustrated in Fig. 8.

3.3.6. Description of P&O method

**Zone I**: the maximum torque of the turbine is less than the nominal torque \( \frac{\Delta T}{\Omega_m} \).

The search for the maximum points depends on whether the quantity \( \frac{\Delta T}{\Omega_m} \) is positive or negative. We increase or decrease respectively the electromagnetic torque by acting on the current (see Eq. (19)). It results respectively an increase or a decrease of the rotational speed. The change of the quantity sign \( \frac{\Delta T}{\Omega_m} \) provides us information about the zero crossing which corresponds to the desired point (Fig. 10).

**Zone II**: the maximum torque of the turbine is greater than the nominal torque.

The search for the optimal point is determined by operating the turbine at its nominal mechanical torque. For this, we compare the
torque of the turbine to the rated nominal torque as follows (Fig. 10).

Depending on whether the difference between the turbine torque and the nominal torque, we increase or decrease respectively the electromagnetic torque by acting on the current (see Eq. (19)). The desired value is obtained when the absolute difference is less than or equal to the desired accuracy.

The advantage of this method is that, it does not require knowledge of the mechanical characteristic of the turbine and the speed of the desired point [24]. However, its disadvantage lies in the oscillation around the desired value.

4. Simulation results and discussion

The dynamic behavior of the wind generator connected to a stable grid is shown in Figs. 11–25. The simulation is carried out by using Matlab/Simulink package and the parameters of DFIG and the wind turbine are respectively given in Tables 1 and 2.

Powers exchanged between the grid and the generator are obtained by stator flux orientation. The simulation results are obtained by forcing to zero the reactive power of the stator and the rotor side of the grid. The reference for the active power injected into the grid is determined by an optimization program. The speed wind profile chosen is represented in Fig. 11.

Fig. 12 depicts the variation range of the DFIG mechanical rotation speed.

The mechanical power evolution as a function of time and the rotational speed is illustrated in Figs. 13 and 14 respectively. Note that powers recovered in the operating mode sub-synchronous and super-synchronous are nonlinear and linear functions respectively.

Power coefficient \( (C_P) \) and tip speed ratio \( (\lambda) \) evolutions are shown in Figs. 15 and 16 respectively. In sub synchronous mode, \( C_P \) fluctuates around its maximum value 0.5 while tip speed ratio fluctuates around its optimal value 5. In super synchronous mode, \( C_P \) decreases to its minimum value, and tip speed ratio increases to its maximum value.

Fig. 17 shows clearly the evolution of the power coefficient versus the specific speed.

The torque on the DFIG shaft is variable in the sub-synchronous operation and is limited to its nominal value in the operating area of super-synchronous (Figs. 18 and 19).

Fig. 20 illustrates the reactive rotor power, and which depends on the sign of the slip (Fig. 21).

In Fig. 22, we have presented the rotor and stator active power injected to the grid which follows their references. Fig. 23 represents the stator reactive power injected to the grid.
Fig. 19. DFIG electromagnetic torque.

Fig. 20. DFIG rotor side reactive power.

Fig. 21. DFIG slip.

Fig. 22. Stator, rotor and grid actives powers.
Fig. 24 represents the voltage and current of a rotor phase which are plotted corresponding to the operating mode sub-synchronous, super-synchronous and near synchronous respectively. Fig. 25 shows the grid side voltage and current, these two values are in the opposition phase.

5. Conclusion

In this paper, the optimization of extracted power from a wind energy conversion system is presented. The solution is based on the exploitation of the power generated by the rotor in super synchronous mode. In this case, we have suggested to fix the turbine torque at its nominal value, leaving the rotor speed and power increase simultaneously. So the rotor speed and the total power can reach twice their nominal values. Using a fast and reliable fully rugged electrical control, we were able to control all the powers involved in such a system while maintaining stator reactive power at zero value and ensuring unity power factor at the input of matrix converter. After the application of the proposed strategy,

<table>
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<tr>
<th>Table 1</th>
<th>Wind generator parameters.</th>
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<tbody>
<tr>
<td>Parameters</td>
<td>Values</td>
</tr>
<tr>
<td>Nominal power</td>
<td>1.5 MW</td>
</tr>
<tr>
<td>Nominal voltage</td>
<td>690 V</td>
</tr>
<tr>
<td>Stator resistance ($R_s$)</td>
<td>0.012 Ω</td>
</tr>
<tr>
<td>Rotor resistance ($R_r$)</td>
<td>0.021 Ω</td>
</tr>
<tr>
<td>Stator ($L_s$) and rotor ($L_r$) inductance</td>
<td>0.0137 H</td>
</tr>
<tr>
<td>Magnetizing inductance ($L_m$)</td>
<td>0.0135 H</td>
</tr>
<tr>
<td>Number of pole pair ($P$)</td>
<td>2</td>
</tr>
<tr>
<td>Friction coefficient ($f$)</td>
<td>0.0071 N m s/rad</td>
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</table>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Wind turbine parameters.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>Values</td>
</tr>
<tr>
<td>Radius ($R$)</td>
<td>36.5 m</td>
</tr>
<tr>
<td>Optimal tip speed ratio $i_{opt}$</td>
<td>5</td>
</tr>
<tr>
<td>Number of blades</td>
<td>3</td>
</tr>
<tr>
<td>Total inertia (Turbine + DFIG), J</td>
<td>500 kg m²</td>
</tr>
</tbody>
</table>

Fig. 24 represents the voltage and current of a rotor phase which are plotted corresponding to the operating mode sub-synchronous, super-synchronous and near synchronous respectively. Fig. 25 shows the grid side voltage and current, these two values are in the opposition phase.
we have shown on one hand, through the different simulation results, the proper functioning of the system in sub synchronous and super synchronous modes. Furthermore, it was shown that the stator active power fluctuates around its nominal value while tip speed ratio increases to its maximum value when the rotational speed reaches twice its nominal value. On another hand, it was also shown that in sub synchronous mode, the power coefficient fluctuates around its maximum value while tip speed ratio fluctuates around its optimal value. In super synchronous mode, the power coefficient decreases to its minimum value and tip speed ratio fluctuates linearly and actually reaches its nominal value when the rotational

References