Power Quality Improvement Using Grid Side Converter of Wind Energy Conversion System

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Abstract: This paper presents the control of a WECS (wind energy conversion system), equipped with a DFIG (doubly fed induction generator), for maximum power generation and power quality improvement simultaneously. The proposed control algorithm is applied to a DFIG whose stator is directly connected to the grid and the rotor is connected to the grid through a back-to-back AC-DC-AC PWM (pulse width modulation) converter. The RSC (rotor side converter) is controlled in such a way to extract a maximum power, for a wide range of wind speed. The GSC (grid side converter) is controlled in order to filter harmonic currents of a nonlinear load coupled at the PCC (point of common coupling) and ensure smooth DC bus voltage. Simulation results show that the wind turbine can operate at its optimum energy for a wide range of wind speed and power quality improvement is achieved.

Key words: Variable speed DFIG, MPPT, wind energy, power quality, active filtering, GSC.

1. Introduction

During the last decade, and to reduce the pollution problem, much efforts have been focused on the development of environmentally friendly sources of energies such as wind and solar. WECS (wind energy conversion system) equipped with DFIG (doubly fed induction generator) has received increasing attention due to its noticeable advantages over other WT (wind turbine) systems. Compared to the fixed speed wind turbine, the variable speed wind turbine can provide decoupled control of active and reactive power of the generator and improve power quality. Due to several integration of nonlinear loads, such as power electronics converters and large alternating current drives, which are polluting sources of the grid, the modern WECS is not only controlled to product active power to the customers but also to improve the power quality and support the grid during any kind of faults.

One can profit of the power electronic converters to provide some of the ancillary services (reactive power absorption or injection to achieve voltage control, harmonic currents compensation). Recently, many groups of researchers have addressed the issue of making use of the WECS converters, connected between the generator and the grid, to improve grid power quality and achieve harmonic currents mitigation. In Ref. [1], Singh et al. have studied the grid synchronization with harmonics and reactive power compensation capability of a permanent magnet synchronous generator-based variable speed wind energy conversion system. In this work, the GSC (grid side converter) is actively controlled to feed generated power as well as to supply the harmonics and reactive power demanded by the non-linear load at the PCC (point of common coupling). In Ref. [2], Gaillard et al. have controlled the RSC (rotor side converter) for reactive power compensation and active filtering capability of a WECS equipped by a DFIG without any over-rating.
In Ref. [3], the RSC is used for compensating the whole harmonic currents or the 5th and 7th harmonic components. In Refs. [2, 3], a HSF (high selectivity filter) has been used to extract particular harmonic currents. In Ref. [4], the RSC is used as an active filter in order to control the power factor and harmonics mitigation of the most significant and troublesome (5th and 7th) components. In Ref. [5], the GSC is used as a shunt active filter to cancel significant harmonics. In Ref. [6], Singh et al. have studied the application of adaptive network-based fuzzy inference system for sensorless control of PMSG-based wind turbine with nonlinear-load compensation capabilities. In this contribution, the GSC has been used as harmonic, reactive power, and unbalanced load compensator. In Ref. [7], Engelhardt et al. have discussed the steady state reactive power loading capability of a DFIG-based WECS by taking into account the most important physical phenomena restricting the reactive power that supply the WECS. In Ref. [8], different combinations of reactive power control of RSC and GSC are investigated. In Ref. [9], Machmoum and et al. have studied flicker mitigation in a DFIG for wind energy conversion based on RSC control.

This paper presents the control of a WECS, equipped by a doubly fed induction generator, for maximum power generation and power quality improvement simultaneously. A speed FLC1 (fuzzy logic controller) is used for MPPT (maximum power point tracking) and ensures maximum power generation. This control strategy is applied to the rotor side converter by using a stator flux oriented strategy and an optimal speed reference which is estimated from the wind speed. Elsewhere, another speed FLC2 (fuzzy logic controller) is used to control the GSC (grid side converter) by using the oriented voltage control strategy in order to ensure a smooth DC voltage and compensate the harmonic currents of a non linear load connected at the PCC. The feasibility and effectiveness of these controls strategies, in terms of active power production and active filtering, have been tested by simulation.

The scheme of the studied wind energy conversion system is presented in Fig. 1. It is formed by the WECS and the non linear load. These elements are connected together at the PCC.

2. Turbine and DFIG Modelling

2.1 Turbine Modelling

The mechanical power captured by the turbine from the wind is given by the following expression:

$$p_r = \frac{1}{2} \rho c_p(\lambda, \beta) s v^3$$  \hspace{1cm} (1)

where $\rho$ is the air density (1.225 kg/m³), $s$ is the area of the wind wheel (m²), $v$ is the wind speed (m/s), $c_p(\lambda, \beta)$ is the power coefficient of the turbine, $\lambda$ is the tip speed ratio and $\beta$ is the pitch angle. The tip speed ratio is given by the following equation:

$$\lambda = \frac{R \omega_t}{v}$$  \hspace{1cm} (2)

where $R$ is the radius of the turbine (m) and $\omega_t$ is the speed turbine (rd/s).

Fig. 2 shows the curve of the power coefficient versus $\lambda$ for a constant value of the pitch angle $\beta$. In the case of a variable speed system, one can let $\omega_t$ changing with the variation of the wind speed $v$ in order to maintain $\lambda$ at its optimal value $\lambda_{opt}$. So the turbine blade can capture the maximum of the wind power.

2.2 Modelling of the DFIG

The DFIG voltage and flux equations, expressed in Park reference frame, are given by the following equations:

$$u_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_L \psi_{qs}$$

$$u_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega_L \psi_{ds}$$

$$u_{dq} = R_r i_{dq} + \frac{d\psi_{dq}}{dt} - (\omega_L - \omega) \psi_{dq}$$

$$u_{qy} = R_r i_{qy} + \frac{d\psi_{qy}}{dt} + (\omega_L - \omega) \psi_{dy}$$

$$\psi_{ds} = L_s i_{ds} + M_{id}$$

$$\psi_{qs} = L_s i_{qs} + M_{iq}$$

$$\psi_{dr} = L_r i_{dr} + M_{id}$$

$$\psi_{qy} = L_r i_{qy} + M_{iq}$$  \hspace{1cm} (3)
The electromagnetic torque is expressed by:

$$T_{em} = \frac{3}{2} p \frac{M}{L_s} (i_{ds}i_{qr} - i_{dr}i_{qr})$$  (5)

The mechanical equation is expressed as follow:

$$T_{em} = J \frac{d\Omega_s}{dt} + f \Omega_s + T_r$$  (6)

where:

- $J$ is the total inertia;
- $\Omega_s$ is the generator speed;
- $f$ is the total mechanical damping coefficient and $p$ is the number of pole pairs;
- $R_s$ and $R_r$ are the stator and rotor phase resistances, respectively.

$\omega_s$, $\omega_r$ are respectively the synchronous angular speed of the generator and the angular speed of the rotor with $\omega_r = p\Omega_g$.

$L_s$ and $L_r$ are respectively the stator and rotor inductances and $M$ is the magnetizing inductance.

$T_r$ is the turbine torque.

### 3. Control of Rotor Side Converter

To achieve the RSC control, the stator flux is set aligned with the $d$ axis and the authors suppose that the grid is assumed to be strong and stable so $\psi_s$ is constant.

Moreover, the stator resistance of the DFIG is neglected. Since the stator flux is aligned with the $d$ axis, we can write $\psi_{ds} = \psi_s$ and $\psi_{qr} = 0$. Hence, Eqs. (3)-(5) become respectively \cite{10, 11}:

$$u_{ds} \approx 0$$  (7.a)

$$u_s = u_{ds} \approx \omega_s \psi_s$$  (7.b)

$$\psi_s = L_s i_{ds} + M i_{qr}$$  (8.a)

$$0 = L_r i_{qr} + M \psi_s$$  (8.b)

$$T_{em} = -\frac{3}{2} p \frac{M}{L_s} \psi_s i_{qr}$$  (9)

where $u_s$ is the stator voltage magnitude assumed to be constant.

From Eq. (9), one can establish that the electromagnetic torque can be controlled directly by acting on $i_{qr}$ current. Then, the current reference is given by:

$$i_{qref} = -\frac{2L_s \omega_r}{3 pu_s M} T_{emref}$$  (10)

The stator reactive power is expressed by the following equation:

$$Q_s = \frac{3}{2} \left( u_{ds} i_{ds} - u_{ds} i_{qr} \right)$$  (11)

Elsewhere, Eqs. (7.b) and (8.a) are used to rewrite the stator reactive power as follow:

$$Q_s = \frac{3}{2} \frac{u_s}{L_s \omega_s} (u_s - M \omega_i i_{qr})$$  (12)

From this latter equation, one can note that the stator reactive power can be controlled by acting on $i_{dr}$. To guarantee unitary power factor at the stator side, the reactive power command must be chosen as $Q_{sref} = 0$. So the direct rotor reference current is expressed as:
The speed fuzzy logic controller includes four parts: fuzzification, fuzzy rule base, reasoning and defuzzification as shown in Fig. 3.

The inputs of the fuzzy controller are the speed error \( e \) and its variation \( \Delta e \).

\[
e = \Omega_{g \text{ref}} - \Omega_g \quad (14)
\]
\[
\Delta e = (1 - z^{-1})e \quad (15)
\]

The output is the increment of the electromagnetic torque.

The control block diagram of the rotor side converter is shown in Fig. 4.

To obtain the output of the FLC, the defuzzification used in this work is based on the center of gravity method. \( k_1, k_2 \) and \( k_3 \) are the normalisation constants.

Furthermore, to extract a maximum of power from the wind and ensure the MPPT, the generator speed is estimated by the following equation:

\[
\Omega_{g \text{opt}} = \delta \frac{\lambda_{\text{opt}}}{R} \quad (16)
\]

With \( \delta \) is the gearbox ratio and \( \lambda_{\text{opt}} = 6.4 \).

The inference matrix is resumed in Table 1.

From Fig. 4, a reference \( i_{q \text{ref}} \) was derived from the speed error \( e \) and its variation \( \Delta e \) by tuning the FLC1, as shown in Fig. 4. Also, to guarantee a unitary power factor at the stator side, the stator reactive power command must be chosen as \( Q_{s \text{ref}} = 0 \), so an appropriate reference current \( i_{d \text{ref}} \) was derived. Then, both \( d-q \) reference currents were transformed to their natural \( abc \) reference frame and used for implementing the hysteresis modulation as shown in Fig. 4.

4. Control of Grid Side Converter

The grid side converter is controlled by a FLC2 in such a way to guarantee a smooth DC voltage.

The control block diagram of this converter is presented in Fig. 5. The inference matrix is the same as that of the speed fuzzy logic controller (FLC1) by replacing \( e \) and \( \Delta e \) with \( e_c \) and \( \Delta e_c \), respectively. The error is given by:

\[
e_c = V_{\text{dc ref}} - V_{\text{dc}} \quad (17)
\]

Also, the variation of the error is expressed by:

\[
\Delta e_c = (1 - z^{-1})e_c \quad (18)
\]

The grid phase voltages can be expressed as follow:

\[
v_{ag} = R_g i_{ag} + L_g \left( \frac{di_{ag}}{dt} + v_{\text{inv}} \right) \quad (19)
\]

By using park transformation, Eq. (19) can be expressed as follows:

\[
v_{ag} = R_g i_{ag} + L_g \left( \frac{di_{ag}}{dt} - \omega_L i_{ag} + v_{\text{inv}} \right) \quad (20)
\]
The active and reactive powers, exchanged between the grid and the GSC, are given by the following equations:

\[
\begin{align*}
P_g &= \frac{3}{2}(v_{dg}i_{dg} + v_{aq}i_{aq}) \\
Q_g &= \frac{3}{2}(v_{aq}i_{aq} - v_{dg}i_{dg})
\end{align*}
\] (21)

If the d-axis is aligned with the stator voltage, one can write: \(v_{dg} = u_s\) and \(v_{aq} = 0\). Hence, the active and reactive powers expressions are easily simplified as follows:

\[
\begin{align*}
P_g &= \frac{3}{2}u_s i_{dg} \\
Q_g &= -\frac{3}{2}i_{aq} u_s
\end{align*}
\] (22)

By neglecting the converter losses, the DC power has to be equal to the active power flowing between the grid and the grid side converter and one can write:

\[
V_{dc} i_{dc} = \frac{3}{2}u_s i_{dg}
\] (23)

The DC capacitor voltage \(V_{dc}\) is controlled by the current \(i_{dc}\) in the voltage vector-oriented reference frame. Thus, a reference current \(i_{dcref}\) was derived from the DC link voltage error \(e_c\) and its \(\Delta e_c\) by tuning the FLC2 controller, as shown in Fig. 5. To control the reactive power \((Q_g)\) to a desired value \((Q_{gref})\), a command current \(i_{aqref}\) is derived from Eq. (22). After a \(d-q\)-abc transformation of these reference currents, hysteresis modulation may then be implemented as shown in Fig. 5.

5. Active Filtering

There are various methods to identify the harmonic currents of a nonlinear load. The most classical methods are “instantaneous power theory p-q” or “d-q or synchronous detection method” [12]. Practically, SPBF (selective pass band filter) or LPF (low pass filter) has been used to extract the harmonic currents components [2]. Frequency domain compensation, which is based on Fourier analysis, is not very used because it requires more real time processing power. In the case, the instantaneous power theory is used as shown in Fig. 6. For being compensated, by the GSC, the resulting \(d-q\) reference harmonic currents \((i_{dh}, i_{qh})\) must be subtracted from the currents \((i_{dgref}, i_{aqref})\) as shown in Fig. 5.

6. Simulation Results

6.1 Maximum Active Power Generation by the MPPT Strategy

In this section, the system is controlled to track its maximum power operating point. Fig. 7 shows the responses for a wind speed in ramp form. The graphs shown correspond (in order of appearance): (1) wind speed; (2) generator speed and its reference; (3) power coefficient. As can be seen from the plots, the generator rotor speed is controlled according to MPPT strategy. Also, the power coefficient is kept around its optimum \(C_{pmax} = 0.4993\). The stator active power is varied according to the MPPT strategy and a unity power factor is ensured at the stator side. Moreover, the reactive power is maintained to zero. The zoom of a stator voltage and the corresponding current shows that the DFIG produces active power to the grid (Fig. 8c).

6.2 Harmonic Mitigation

The performance of the WECS, in terms of active filtering, is now studied under the nominal stator active power \((P_{sn} = 7.5 \text{ kW})\) for a nominal wind speed of 11 m/s. The considered nonlinear load, coupled at the PCC,
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Fig. 6 Extraction of the harmonic components using instantaneous power algorithm [3].

Fig. 7 MPPT power generation: (a) filtered wind speed (m/s); (b) actual rotor speed and its reference (rd/s); (c) power coefficient.

is formed by a full bridge diode rectifier as shown in Fig. 1. The main goal is to eliminate the harmonic currents of the non linear load which has a harmonic distortion ratio of 29%.

Figs. 9 and 10 show the simulation results. Fig. 9 shows the current waveforms, before and after active filtering at $t = 0.2$ s. The waveforms: grid current ($i_G$) and the GSC current ($i_{ag}$) show clearly the performance of the proposed strategy in terms of active filtering. The DC capacitor voltage is maintained constant by the control of the GSC as shown in Fig. 9c. After filtering, one notice small oscillations of $V_{dc}$ at the 300 Hz. However, these oscillations do not affect the DC bus stability.

Fig. 8 MPPT power generation: (a) stator active power $P_s$ (W), reactive power $Q_s$ (Var); (b) stator phase voltage $V_{as}$ (V) and stator phase current $i_{as}$ (A); (c) zoom of the phase stator voltage and the corresponding current.

Fig. 9 Waveforms before and after active filtering at $t = 0.2$ s: (a) grid current ($i_G$) (A); (b) phase GSC current $i_{ag}$ (A); (c) DC voltage $V_{dc}$ (V).
Fig. 10  Grid current spectrum: (a) before active filtering; (b) after active filtering at \( t = 0.2 \) s.

Fig. 10 shows the grid current spectrum before and after harmonics compensation. The grid current THD (total harmonic distortion) has been reduced from 13\% to about 7.5\%. After compensation, one can note that the most significant (5th and 7th) harmonic current components have been considerably reduced as shown in Figs. 10a and 10b. In fact, the RMS of the 5th and the 7th harmonic components has been reduced from about 0.92 A to 0.34 A and from 0.62 A to 0.11 A, respectively.

7. Conclusions

This paper has discussed the control of a WECS equipped by a DFIG for active power generation and active filtering. The RSC has been controlled, using a speed fuzzy logic controller, in order to ensure a smooth DC. Small oscillations, of the DC bus voltage at the 300 Hz, have been observed. However, these oscillations did not affect its stability.

References


Appendix

Table 2 Wind energy conversion system parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td><strong>Turbine parameters</strong></td>
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<tr>
<td>Power (kW)</td>
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<tr>
<td>Number of blades</td>
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<tr>
<td>Turbine radius, $R$ (m)</td>
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<tr>
<td>Gearbox ratio</td>
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<tr>
<td><strong>DFIG parameters</strong></td>
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<td>Power (kW)</td>
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<td>Stator resistance, $R_s$ (Ω)</td>
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<td>Rotor resistance, $R_r$ (Ω)</td>
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<td>Rotor phase inductance, $L_r$ (H)</td>
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<td>Friction factor, $f$ (N m s)</td>
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