Wind System Based on a Doubly Fed Induction Generator: Contribution to the Study of Electrical Energy Quality and Continuity of Service in the Voltage Dips Event

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Abstract- Industrial machines are very sensitive to electrical defects especially the Doubly Fed Induction Generators. This high sensitivity reveals many difficulties in terms of compliance with the specifications imposed by the electrical grid operators. This article gives a proposed strategy to control the whole wind conversion chain which allows to obtain high production performances in perturbed conditions (the voltage dips). To do this, a comparison between two control strategies, one conventional and the other modified, is presented to conclude about which one guarantees a good electrical energy quality and continuity of service in the voltage dips event. The results of this work are provided by simulations in the MATLAB / SIMULINK environment.

Keywords Conventional Control Strategy, Doubly Fed Induction Generator (DFIG), Modified Control Strategy, Voltage Dips, Wind Turbine.

1. Introduction

Voltage dip may cause very harmful problems even if it is relatively small. This defect for the industrialist and entrepreneurs means, production stoppages, overtime for restarting processes which causes performances degradation. And to have a close idea about the disturbance costs; the dissatisfaction of customers, the risks to the safety and security of staff and of the production tools, the loss of data, etc, must also be considered [15].

To avoid all the consequences mentioned before, and any instability in the production of electrical energy, a continuation of wind turbine production even in disturbed conditions, must be assured.

The objective of this research article is to propose a control strategy of the generator that can improve the performances of the wind systems in the case of a disturbed electrical grid. The emphasis is on the comparison of two stator flux control strategies (conventional and modified) of the DFIG (Doubly Fed Induction Generator) [2], [3]. On the one hand, the conventional approach allows to obtain the mode of operation sought by positioning in an optimal way the currents vectors and the resulting flows vectors. On the other hand, the modified approach considers the dynamics of the stator flux [3]. The fault current in the rotor windings and the overvoltage in the DC bus are limited due to the proposed control strategy.

The wind generator used is a three-axis horizontal wind turbine using a Doubly Fed Induction Generator (DFIG).

Nomenclatures

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
</tr>
<tr>
<td>$C_r$</td>
<td>Resistive torque (N.m)</td>
</tr>
<tr>
<td>$C_{aer}$</td>
<td>Aerodynamic torque (N.m)</td>
</tr>
<tr>
<td>$C_{mec}$</td>
<td>Mechanical torque (N.m)</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>Turbine speed (Rad/s)</td>
</tr>
</tbody>
</table>
Let’s recall the differential equations system of the machine [4]:

\[ V_{sd} = R_s I_{sd} - \omega_s \psi_{sd} + \frac{d\psi_{sd}}{dt} \]  
\[ V_{sq} = R_s I_{sq} + \omega_s \psi_{sq} + \frac{d\psi_{sq}}{dt} \]  
\[ V_{rd} = R_r I_{rd} - \omega_r \psi_{rd} + \frac{d\psi_{rd}}{dt} \]  
\[ V_{rq} = R_r I_{rq} + \omega_r \psi_{rq} + \frac{d\psi_{rq}}{dt} \]

- Flux’s relations:

\[ \psi_{ad} = L_s I_{ad} + M I_{rd} \]  
\[ \psi_{aq} = L_s I_{aq} + M I_{rq} \]  
\[ \psi_{rd} = L_r I_{rd} + M I_{rd} \]  
\[ \psi_{rq} = L_r I_{rq} + M I_{rq} \]

A vector control of this machine was designed by orienting the Park’s frame, so that the stator flux along the d axis is constantly zero (\( \psi_{sq} = 0 \)), which simplifies the DFIG obtained model and the resulting control device [5]. Equations (1 and 2) become:

\[ \frac{d\psi_{ad}}{dt} = V_{ad} - R_s I_{ad} \]  
\[ V_{aq} = R_s I_{aq} + \omega_s \psi_{ad} \]
\[
\frac{d\psi_{sd}}{dt} = V_{sd} - R_s I_{rd} + \omega_r \psi_{rq} \tag{11}
\]
\[
\frac{d\psi_{rq}}{dt} = V_{rq} - R_s I_{rq} - \omega_r \psi_{sd} \tag{12}
\]

From the equations of the direct and quadrature stator flux components, we obtain the following expressions of the stator currents [5]:
\[
I_{sq} = -\frac{M}{L_s} I_{rq} \tag{13}
\]
\[
I_{sd} = \frac{\psi_{ad} - M I_{id}}{L_s} \tag{14}
\]

These stator currents are replaced in the equations of the direct and quadrature rotor fluxes components (7 and 8):
\[
\psi_{rd} = L_r \sigma I_{rd} + \frac{M}{L_s} \psi_{ad} \tag{15}
\]
\[
\psi_{rq} = L_r \sigma I_{rq} \tag{16}
\]

\(\sigma\) is the dispersion coefficient between the dq windings:
\[
\sigma = 1 - \frac{M^2}{L_s L_r} \tag{17}
\]

By replacing the expressions of the direct and quadrature stator currents components (13 and 14) in equations (9 and 10) and the expressions of the direct and quadrature rotor fluxes components (15 and 16) in equations (11 and 12), [2], [3], [6], we obtain:
\[
V_{sd} = R_s \frac{L_s}{L_s} \psi_{sd} - \frac{R_s}{L_s} M I_{id} + \frac{d\psi_{ad}}{dt} \tag{18}
\]
\[
V_{rq} = R_s \frac{L_s}{L_s} M I_{rq} + \omega_r \frac{L_s}{L_s} \psi_{sd} \tag{19}
\]
\[
V_{rd} = R_r I_{rd} + L_r \sigma \frac{dI_{rd}}{dt} + \frac{M}{L_s} \frac{d\psi_{ad}}{dt} - L_r \omega_r \sigma I_{rd} \tag{20}
\]
\[
V_{rq} = R_r I_{rq} + L_r \sigma \frac{dI_{rq}}{dt} + L_r \omega_r \sigma I_{rd} + \omega_r \frac{M}{L_s} \psi_{ad} \tag{21}
\]

The rotor equations (20 and 21) permit to determine the rotor currents:
\[
\frac{dI_{rd}}{dt} = \frac{1}{L_s \sigma} (V_{rd} - R_r I_{rd} - e_q) \tag{22}
\]
\[
\frac{dI_{rq}}{dt} = \frac{1}{L_s \sigma} (V_{rq} - R_r I_{rq} - e_d - e_q) \tag{23}
\]

Where the EMFs are defined as:
\[
e_q = L_r \omega_r \sigma I_{rq} + \frac{M}{L_s} \frac{d\psi_{ad}}{dt} \tag{24}
\]
\[
e_d = L_r \omega_r \sigma I_{rd} \tag{25}
\]

The torque's expression:
\[
T_{em} = p (\psi_{sd} I_{rq} - \psi_{sq} I_{rd}) \tag{27}
\]

By orienting the stator flux \((\psi_{sq} = 0)\), we obtain a simplified torque expression:
\[
T_{em} = p \psi_{ad} I_{sq} \tag{28}
\]

By using the equation (13), The torque then becomes proportional to the quadrature axis current component [2], [3], [6], thus the torque control is carried out from the current \(I_{rq}\) regulation:
\[
T_{em} = -p \frac{M}{L_s} \psi_{ad} I_{rq} \tag{29}
\]

The direct stator voltage component is close to zero. Thus, the reactive power can be described by:
\[
Q_s = V_{sq} I_{sd} = \frac{V_s}{L_s} \frac{\psi_{sq}}{L_s} - \frac{V_s M}{L_s} I_{rd} \tag{30}
\]

We remark that the reactive power can be controlled by regulating the direct rotor current component \(I_{rd}\).

Remarks:
- By chosen the dq axes as a reference \((\psi_{ad} \text{ is maintained constant})\), the electromagnetic torque produced by the DFIG and consequently the stator power become proportional to the quadrature component of the rotor current \(I_{rq}\).
- The stator reactive power is not proportional to the direct rotor current due to a constant imposed by the grid \(V_s \psi_{ad} / L_s\).
- The two stator powers can be controlled independently.

2.2. Control strategy of the DFIG rotor currents

The simplified representation of the current regulation in a block diagram form is given in Fig. 2.

At the end of these settings, we obtain \(I_{rq} = I_{rq-ref}\) and \(I_{rd} = I_{rd-ref}\) with a chosen response time (the speed loop response time chosen to be superior to the currents response time) [2], [3].

2.2.1. Flux estimation

The direct stator flux component is written by:
2.3. Control strategy of the grid connection

The purpose from controlling the GSC is to maintain a constant DC bus voltage whatever the amplitude and the direction of power, and to guarantee a required power factor.

The GSC controls the currents flown by the filter and the vector control allows an independent and decoupled control of the active and reactive powers circulating between the grid and the GSC. The currents are controlled by two regulators which generate the applied voltages references \((V_{md-ref} \text{ and } V_{mq-ref})\). The quadrature axis current is used to regulate the DC bus voltage and the direct axis current to regulate the reactive power [2], [3], [9].

2.3.1. Control strategy of the currents sent to the grid

The filter model can be simplified by the following equations:

\[
V_{md} = R_t I_{td} + L_t \frac{dI_{td}}{dt} - e_{iq} \quad (34)
\]
\[
V_{mq} = R_t I_{tq} + L_t \frac{dI_{tq}}{dt} + e_{id} + V_s \quad (35)
\]

Where,

\[
e_{iq} = L_t \omega_s I_{tq} \quad (36)
\]
\[
e_{id} = L_t \omega_s I_{td} \quad (37)
\]

\(R_t\) and \(L_t\) are the filter resistance and inductance respectively.

We can set up a control of the circulating currents in the RL filter, assuring a decoupled control for each axis. The RL filter currents of the dq axes are the controllers reference’s values [2], [3].

\(I_{tq-ref}\) and \(I_{td-ref}\) are respectively derived from the control block of the DC bus voltage and the reactive power control [2], [3].

The control device contains three specific actions:

- A voltage compensation:
  \[
e_{iq-ref} = L_t \omega_s I_{tq} \quad (38)
  \]
  \[
e_{id-ref} = L_t \omega_s I_{td} \quad (39)
  \]

- A decoupling action of the currents:
  \[
  V_{md-ref} = V_{bd-ref} - e_{tq-ref} \quad (40)
  \]
  \[
  V_{mq-ref} = V_{bd-ref} + e_{td-ref} + V_{sq} \quad (41)
  \]

- Closed loop control of currents:
  \[
  V_{bd-ref} = C_t (i_{td-ref} - i_{td}) \quad (42)
  \]
\[ V_{bq-ref} = C_I (i_{tq-ref} - i_{tq}) \]  (43)

### 2.3.2. Power control

By neglecting \( R_t \) and considering \( V_{ad} = 0 \), the powers exchanged through the filter to the grid become:

\[ P_t = V_{tq} I_{tq} \]  (44)
\[ Q_t = V_{tq} I_{td} \]  (45)

We obtain \( I_{tq-ref} \) and \( I_{td-ref} \) from the previous relations:

\[ I_{tq-ref} = \frac{P_{t-ref}}{V_{tq}} \]  (46)
\[ I_{td-ref} = \frac{Q_{t-ref}}{V_{tq}} \]  (47)

\( I_{td-ref} \) is used to control the reactive power at the GSC connection point with the electrical grid. \( I_{tq-ref} \), for its part, is used to maintain the DC bus voltage constant. With this principle, a null reference reactive power can then be imposed \( Q_{t-ref} = 0 \) VAR.

#### 2.3.3. DC bus control

From \( I_c = I_{gm} - I_{gm} \), we can express the powers involved in the DC bus:

\[ P_r = U R_{eff} \]  (48)
\[ P_c = U R_{eff} \]  (49)
\[ P_g = U R_{eff} \]  (50)

These powers are linked by the relation:

\[ P_g = P_r + P_c \]  (51)

If we neglect all Joules losses (losses in the capacitor, the converter and the RL filter), the power outcoming from the grid \( P_t \) corresponds to the power outcoming from the DC bus added to the power appearing in the rotor circuit \( P_r \), in hypersynchronous mode:

\[ P_t = U I_{dc} + P_r \]  (52)

The capacitor current is used to regulate the DC bus voltage by a PI controller.

The block diagram of the corresponding control is shown in Fig. 3. The voltages are then sent to a PWM modulator.

### 3. Modified Vector Control Strategy of the DFIG

In the conventional vector control the flux is taken as a constant to simplify the dimensioning of the current controllers while controlling the DFIG. However, during a voltage dip, the stator flux will decrease because the stator is directly connected to the grid. Moreover, the calculation of the Park’s orientation frame may be distorted during the voltage dip. As a solution, the stator flux dynamics must not be neglected during the dimensioning of the current controllers [3].

The stator flux components are expressed as:

\[ \psi_{sd} = L_s I_{sd} + M I_{rd} \]  (53)
\[ \psi_{sq} = L_s I_{sq} + M I_{rq} \]  (54)

During a voltage dip, the quadrature stator flux component is not null. This implies that the stator currents are obtained by:

\[ I_{sq} = \frac{\psi_{sq} - M I_{rq}}{L_s} \]  (55)
\[ I_{rd} = \frac{\psi_{rd} - M I_{rq}}{L_s} \]  (56)

By replacing these equations in the expressions of the rotor fluxes, we obtain:

\[ \psi_{rd} = L_s \alpha I_{rd} + \frac{M}{L_s} \psi_{sd} \]  (57)
\[ \psi_{eq} = L_r \alpha I_{eq} + \frac{M}{L_s} \psi_{sq} \]  
\[ (58) \]

By replacing the currents equations (55 and 56) in the expressions of the stator voltages (1 and 2) we obtain:

\[ V_{sd} = \frac{R_s}{L_s} \psi_{sd} - \frac{R_r}{L_r} M I_{rd} + \frac{d\psi_{sd}}{dt} \]  
\[ (59) \]

\[ V_{sq} = \frac{R_s}{L_s} \psi_{sq} - \frac{R_r}{L_r} M I_{rq} + \frac{d\psi_{sq}}{dt} \]  
\[ (60) \]

And by replacing the expressions of the rotor flux (57 and 58) in the expressions of the rotor voltages (3 and 4), we obtain:

\[ V_{rd} = R_s I_{rd} + L_r \sigma \frac{dI_{rd}}{dt} + e_q + e_{qd} \]  
\[ (61) \]

\[ V_{rq} = R_s I_{rq} + L_r \sigma \frac{dI_{rq}}{dt} + e_d + e_{dq} \]  
\[ (62) \]

with:

\[ e_q = -L_r \alpha, \sigma I_{eq} \]  
\[ (63) \]

\[ e_d = L_r \alpha, \sigma I_{rd} \]  
\[ (65) \]

\[ e_{qd} = \frac{M}{L_s} (-\alpha, \psi_{sq} + \frac{d\psi_{sq}}{dt}) \]  
\[ (66) \]

\[ e_{dq} = \frac{M}{L_s} (\alpha, \psi_{sd} + \frac{d\psi_{sd}}{dt}) \]  
\[ (67) \]

From these equations, we can dimension a PI controller for the rotor currents. It should be noted that for a correct control the stator flux and its dynamics \( \frac{d\psi_{rd}}{dt}, \frac{d\psi_{eq}}{dt} \) must be compensated during the voltage dip.

### 4. Simulation Results

To study the influence of the voltage dips on the proposed strategy, a three-phase voltage dip of 20% and for duration of 100 ms is applied to the DFIG. The system model and its control were simulated using Matlab/Simulink considering a 1.5 MW DFIG and a constant wind speed of 13 m/s. The system parameters are summarized in Table 1, Table 2 and Table 3.

<table>
<thead>
<tr>
<th>DFIG Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Power</td>
</tr>
<tr>
<td>Stator Resistance ( R_s )</td>
</tr>
<tr>
<td>Rotor Resistance ( R_r )</td>
</tr>
<tr>
<td>Stator Inductance ( L_s )</td>
</tr>
<tr>
<td>Magnetization Inductance ( M )</td>
</tr>
<tr>
<td>Rotor Inductance ( L_r )</td>
</tr>
<tr>
<td>Number of pole pairs ( P )</td>
</tr>
<tr>
<td>Friction Coefficient ( f )</td>
</tr>
<tr>
<td>Power Supply Frequency ( F )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wind turbine parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade number</td>
</tr>
<tr>
<td>Blade radius ( R )</td>
</tr>
<tr>
<td>Gear-box gain ( G )</td>
</tr>
<tr>
<td>Inertia ( J )</td>
</tr>
</tbody>
</table>

| Table 1. DFIG and wind turbine Parameters |

| Table 2. Parameters of the different wind system commands |

<table>
<thead>
<tr>
<th>Rotor currents control</th>
<th>Time constant in closed loop ( \tau = 1 ms )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_i = \frac{R_r}{\tau} )</td>
<td>( K_i = 21 )</td>
</tr>
<tr>
<td>( K_p = \frac{\sigma L_r}{\tau} )</td>
<td>( K_p = 0.297 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Filter currents control</th>
<th>Time constant in closed loop ( \tau = 1 ms )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_i = \frac{R_r}{\tau} )</td>
<td>( K_i = 2.4 )</td>
</tr>
<tr>
<td>( K_p = \frac{L_r}{\tau} )</td>
<td>( K_p = 5 )</td>
</tr>
</tbody>
</table>

| DC bus voltage control | Damping factor: \( \xi = 0.707 \)
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_p = 2 \xi \coth \omega_n )</td>
<td>( \xi = 0.167 )</td>
</tr>
<tr>
<td>( K_i = \coth^2 \omega_n )</td>
<td>( K_i = 3.2076 )</td>
</tr>
</tbody>
</table>

Fig. 4. The DFIG modified vector control strategy

Table 2. Parameters of the different wind system commands
Table 3. Parameters of the RL filter and the DC bus

<table>
<thead>
<tr>
<th>Parameters of the RL filter</th>
<th>Parameters of DC bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance $R_t$</td>
<td>$0.012 , \Omega$</td>
</tr>
<tr>
<td>Inductance $L_t$</td>
<td>$0.005 , \text{H}$</td>
</tr>
<tr>
<td>Capacitor $C$</td>
<td>$C=0.0044 , \text{F}$</td>
</tr>
<tr>
<td>Voltage $U_{dc}$</td>
<td>$U_{dc}=1200 , \text{V}$</td>
</tr>
</tbody>
</table>

When the fault occurs at $t=0.6s$, the generator voltage drops for a duration of $t=100\, \text{ms}$ and it gets back to its reference at $t=0.8s$ as shown in figure 5. The voltage dip fault leads to decrease the stator flux and it causes a non-stability which means the stator flux in the quadrature axis cannot be maintained at zero. That is why, the stator flux and its dynamics cannot be neglected.

Fig. 5. The grid voltages during a three-phase voltage dip

The stator currents have different amplitudes during the voltage dip. The fault current amplitude obtained between $t=0.6s$ and $t=0.8s$ with the classical (conventional) approach Fig. 6(b) is higher than the amplitude obtained with the modified approach during the fault Fig. 6(a). The generated amplitude depends on the saturation curve of the generator.

In practice, the currents generated during a voltage dip are reduced after their detection by means of a short-circuit system located at the rotor.

The fact of having an imbalance of the three-phase stator currents strongly causes an imbalance in the total current sent by the DFIG.

The amplitude of the three-phase rotor currents has been modified during the voltage dip. At $t=0.6s$ the conventional control can’t keep the rotor currents at their steady state value as shown in Fig. 7(b). The rotor currents amplitude during the fault is lower with the modified control strategy Fig. 7(a).

As shown in Fig. 8 the DC bus voltage is oscillating with a smaller amplitude with the modified control, this is due to the stator flux dynamics consideration. These oscillations affect the total active powers sent to the grid.

Fig. 8. DC bus voltage during a voltage dip
With the same wind profile, the active powers exchanged with the grid are different when the stator flux is changed during the fault (the same remark about the mechanical speed). We obtain a higher power with the modified approach than with the conventional approach Fig. 9. It can also be noted that the decrease of this power during the voltage dip is greater using the conventional approach.

Fig. 9. The stator active powers

The total reactive power is oscillating with a bigger amplitude using the conventional method Fig. 10. The reactive power using the modified control is close to zero to maintain a unit power factor Fig. 10.

Fig. 10. The stator reactive powers

5. Conclusion

The work carried out in this article had as an objective the elaboration of a complete control strategy of the wind turbines using a DFIG in the normal (stable) electrical grid and abnormal (voltage dip) cases. To achieve this objective, for the normal case a conventional vector control has been presented to show the machine remarkable performances. A decoupled control of the active and reactive powers (also of the power factor) has been obtained and improved the quality of the energy supplied to the grid.

Then a modified vector control strategy of the device was proposed, which considers the stator flux dynamics. The fault current in the rotor windings and the overvoltage in the DC bus are limited due to the proposed control strategy.

Simulations under Matlab/Simulink environment were performed to compare the voltage dips effect on the wind generation system using the two strategies already developed.

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