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Modeling of doubly fed induction generator (DFIG) equipped wind turbine for dynamic studies

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Abstract- The paper is aimed at presenting the dynamic behaviour of a wind turbine equipped with a doubly fed induction generator (DFIG) in case of disturbances in the interconnected grid. A model of a DFIG is presented and adapted for analyzing the response of the wind generator to voltage control, frequency control, voltage sags and wind variations. Simulations, performed by a widely used power system analysis code, are reported and commented.

Index Terms – Wind turbine, Doubly fed induction generator, Low voltage ride through, Voltage regulation, Frequency regulation.

I. INTRODUCTION

Wind energy production is growing worldwide. Its contribution has become significant in the last years, moreover some countries satisfy part of their energy needs by wind turbines. However the integration of this energy source must be properly controlled, so that wind turbines become truly reliable [1].

Wind farms installed until few years ago were not required to satisfy any grid requirements and so, for example, were allowed to disconnect during voltage sags. However, growing the percentage of wind produced electric power, it is no more acceptable that wind farms provide no ancillary services.

The last release, attachment 6, of the Italian standards CEI 11-32 [3] recommends that new wind installations should be able to provide ancillary services such as:

- Primary voltage regulation
- Primary power/frequency semi-regulation
- Power ramp capability
- Remote control of single turbine

The first point means that the generator must have the possibility to regulate the power factor at the high voltage side of the machine transformer between 0.95 lag to 0.95 lead.

The second one obliges the generator to reduce its power output, if the frequency increases above a certain value (50.3 Hz for example), with a certain slope as if it had a droop included in the range 2÷5%.

The power ramp capability means that, when the turbine is connected to the grid, its power flow must not exceed 20% of the rated power per minute. In case of a wind farm this requirement can be fulfilled even connecting each turbine at once; it is however necessary that the global wind farm power output respects the limit mentioned before. Hence every turbine must be totally controlled by remote control centre so in case of grid problems the TSO can disconnect the turbines or require a voltage support as told before.

Moreover all turbines must have the so called low voltage ride through capability, it means that they have to remain connected to the grid even in the case of severe faults that could dip the voltage near to zero [4]. This requirement is already satisfied by all the turbines installed in the last few years even if there is not an international agreement on the voltage characteristic.

In this paper a model of the most common type of wind turbine today installed, the DFIG, is presented [5]. Some simulations that show the behaviour of the model in the before mentioned requirements are reported after a description of the model.

II. CONTROL SCHEME OF THE DFIG&ROTOR SIDE CONVERTER

Fig. 1 shows the blocks diagram, realized in DlgSILENT [6], that describes the prime mover dynamics and the control system of the DFIG&Rotor Side Converter [7].

The blocks can be regrouped into four macro-blocks that describe, in order from left to right, the dynamics of the:

a) Maximum Power Tracking (black rectangle)
b) Prime Mover (blue one)
c) Rotor Converter Control (red one)
d) Generator&Rotor Converter (green one)
Other blocks contain measurement points, matrix reference transformation and the protection system.

Hereafter a brief description of each of them will be given.

A. Maximum Power Tracking (MPT)

The MPT is a characteristic that allows the control system to follow, all the times the wind blows slower than the nominal turbine wind speed, the maximum generation of electric power. Actually it is the curve, shown in Fig. 2, that generates the reference power in function of the rotational speed of the turbine. In theory it would be better to express the reference power in function of the wind speed, which, unfortunately, cannot be measured with accuracy. So, instead of using wind speed, another control variable, the rotational speed of the turbine is used.

As long as the speed of the turbine is lower than the nominal speed (24 rpm, 1.1 on machine base) the curve of the MPT (blue curve) follows the one determinate by the optimum Tip Speed Ratio, \( \lambda \) (TSR – dash curve). When the wind speed approaches the nominal wind speed it is no more necessary to track the maximum power coefficient, rather it has to be reduced, by pitching the blades, because the power in the wind stream is greater than the one that can be converted by the generator.

Fig. 2. Maximum Power Tracking Characteristic (full line) and theoretical Characteristic (dash line)

For the blade profile chosen, the optimum \( \lambda \) is 7.2 and provides a maximum power coefficient, \( c_{p} \), equal to 0.44. The curves of Fig. 3 show the \( c_{p} \) as a function of the tip speed ratio and of the blades pitch angle, \( \beta \). This function is analytically described by the following equations [1]:

\[
C_{p}(\lambda, \beta) = c_{1} (\frac{C_{2}}{\lambda} - c_{3} \beta - c_{4} \beta^{2} - c_{5}) \exp\left(-\frac{c_{6}}{\lambda}\right) \tag{1}
\]

\[
\lambda = \left[ \frac{1}{1 + c_{7} \beta} \right]^{-1} \tag{2}
\]

Where the constants values are:

<table>
<thead>
<tr>
<th>( C_{1} )</th>
<th>( C_{2} )</th>
<th>( C_{3} )</th>
<th>( C_{4} )</th>
<th>( C_{5} )</th>
<th>( C_{6} )</th>
<th>( C_{7} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.73</td>
<td>151</td>
<td>0.58</td>
<td>0.004</td>
<td>2.14</td>
<td>13.2</td>
<td>0.02</td>
</tr>
<tr>
<td>18.4</td>
<td>-0.02</td>
<td>-0.003</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

At last there is a block called Multiplier Power that realizes the primary power/frequency semiregulation. In the block diagram the semi-regulation is represented by a coefficient that multiplies the signal of reference power. This coefficient is equal to 1 if the frequency is between 47.5 Hz and 50.3 Hz, then reaches linearly 0.4 when the frequency values 51.5 Hz. The result is as if the generator had a droop of 4%.

B. Prime Mover (PM)

The PM rectangle includes four blocks. From left to right there is the Pitch Control that simulates the behaviour of the servomechanisms that commands the regulation of the blades pitch angle. Whenever the turbine speed exceeds the reference speed, 24 rpm for this machine, the control system orders the pitching of the blades until the speed is decreased.

The block named Wind Events generates an equivalent wind seen by the hub of the turbine. The normalized power spectrum is shown in Fig. 4. It describes a wind with modest turbulence intensity (10%) in a non excessively rough terrain (hill). Moreover it considers the tower shadow effect, represented by a sinus whose frequency is proportional to the turbine speed and whose amplitude is equal to 3% of the wind speed.

Fig. 3. Power Coefficient in function of the Tip Speed Ratio and parametrized according to the pitch angle

Fig. 4. Normalized wind power spectrum

The block Turbine contains the aerodynamic characteristic of the blades that is the one represented by the curves shown in Fig. 3.

In the end the block Shaft describes the dynamic behaviour of a double shaft system. In fact whenever there is a sudden difference between mechanical and electrical torques the two shafts, the slower one of the turbine and the faster one of the generator, have the possibility to rotate one against the other. That is because the gearbox does not offer a stiff coupling between the two shafts.
C. Rotor Converter Control
The two blocks included in this section model the control of the rotor side converter, that is realized by two pairs of proportional-integral (PI) regulators in cascade. This configuration allows to control separately the active power, which is measured at the connection point of the high voltage side of the transformer, and the reactive power, which is measured at the connection point of the stator of the generator. The control is realized in the stator flux reference frame and so the d-axis regulates the reactive power while the q-axis the active one. In such reference frame the active power (function of the electromagnetic torque) is function of the q-component of the rotor current, while the reactive power is expressed as function of the d-component of the rotor current.

The task of the first stage of PI regulator (PQ Control block) is to generate the references of current by the comparison of the produced powers with their references. The reference of the active power comes from the MPT while the reference of the reactive power has been set to zero. The control of the reactive power is in fact totally demanded to the other converter as it will be seen further.

The second stage of PI controllers (Current Control block) instead manages the modulation signals that command the turn on and off of the switches. The current references are compared with the measured one and the PWM signals are so generated. These references are then transformed in the rotor reference frame because the model of the DFIG is expressed in this reference frame.

D. Generator & Rotor Converter
The model of the DFIG is prebuilt in DiGILENT environment [6], [7]. It is described by a fifth order model with no saturation. The input of the block are the modulation signal for the converter and the shaft power. The outputs instead are speed, stator flux, rotor current and angle reference frame.

E. Other Blocks
Beyond the two blocks for the reference frame transformation (from stator flux to rotor voltage and vice-versa), there are two measurement points where the following electric variables are measured:

1. At the transformer high voltage side, the voltage, the frequency and the active power.
2. At the generator stator connections the reactive power.

At last there is the Protection block, whose task is to open the breaker of the transformer whenever the voltage remains under 0.6 pu for more than 1 second and under 0.8 pu for more than two seconds. The protection block is responsive even in case of overvoltages (higher 1.1 pu for more than 1 second) and under and overspeed, the last one set at 29 rpm (1.283 on machine base). In the end it commands the insertion of the crowbar, that short circuits the rotor windings, whenever the current is greater than 2 kA.

III. CONTROL SCHEME OF THE GRID SIDE CONVERTER
Fig. 5 shows the blocks diagram that describes the control system of the Grid Side Converter.
Here the blocks can be regrouped into three macro-blocks that simulate, in order from left to right, the dynamics of the:

a) Reactive Power Management (black rectangle)
b) Grid Side Converter Control (red one)
c) Grid Side Converter (green one)

The other blocks contain measurement points and matrix reference transformation. A brief description follows.

A. Reactive Power Management
The reactive power management is totally demanded to the grid side converter, that offers a remarkable value. In fact the grid side converter is always connected to the grid and so the reactive power (and hence the voltage at the transformer) can be controlled even during severe faults that could cause the intervention of the crowbar and hence the block of the rotor side converter. Moreover a voltage support can be offered even when the turbine is stand still.

Hence the voltage control is realized in the block named V/Q Characteristic, which generates the reactive power reference signal as follow: if the voltage is below 0.94 pu or above 1.06 pu the block commands the maximum reactive power (respectively lead or lag) that can be handled by the converter. The value drops linearly to zero when the voltage approach the range that includes 0.99 and 1.01 pu.

B. Grid Side Converter Control
This control is very similar to the one of the rotor converter. It has two pairs of PI regulators to control separately, by the d and q-axis, the voltage of the dc link and the reactive power.

About the control of the dc voltage, the first stage of PI is realized in the block DC Voltage Control where the voltage measured is compared with its reference value (1.1, kept constant because there is no interest in changing it). The output is the reference value of current in the d-axis.

The control of the reactive power is realized in the block Q Control instead, where, by the comparison of the reactive
power produced with its reference (function of the voltage at the high voltage side of the transformer, as seen before), the reference current on the q-axis is generated. Subsequently the currents that are flowing through the converter, separated in the d and q-axis in the grid converter voltage reference frame, are compared with their reference in the block named Current Control. The outputs of this block are the commands of modulation of the converter.

C. Grid Side Converter

The model of the PWM Converter, prebuilt in DIgSILENT, represents a self-commutated, voltage sourced AC/DC converter with capacitive circuit. The converter works in the system reference frame while its control is in the grid converter voltage reference frame.

D. Other blocks

Two blocks are used to operate transformations from the system reference to the grid converter voltage reference and vice-versa. Moreover there are three points where the following electric variables are measured:

1. At the transformer high voltage side, the reactive power.
2. At the bus where the capacitor is connected, the dc link voltage.
3. At the connection point of the grid converter, the current flowing versus the autotransformer.

IV. SIMULATION RESULTS

The presented model has been tested by means of some simulations aimed at studying the behaviour during: (a) turbulent wind condition, (b) voltage sags, (c) short circuits, (d) frequency variations.

The plant considered is composed by three turbines located about 300 meters each other and sited in an hilly terrain. The electric diagram of each wind turbine is shown in Fig. 6.

A. Turbulent wind condition

The results hereafter show the behaviour of the simulated turbine in condition of an hypothetical wind with low turbulence. Fig. 7 shows the single turbine and the plant active powers production in pu (the single machine on 1 MVA base, while the global plant on a 3 MVA base) in function of the three wind speeds shown in the first following diagram.

![Fig. 7. Wind speeds (in m/s); Active power production of the single turbine and of the plant (bolder line)](image)

To take into account the distance between the turbines and hence the fact that the three hubs will not see the same wind, it is assumed that the same wind is delayed of 20 seconds between each turbine. As it can be seen the total plant power production benefits from these delays, its course in fact is more smoothed than the course of the single turbine power production. A larger number of turbines would bring further benefits.

Fig. 8 shows some mechanicals variables like the torques (both electrical and mechanical) and the shaft speed of one turbine in function on the wind profile shown before.

![Fig. 8. Wind speeds (blue line, in m/s) and Pitch angle (black, in degree); Electric (red line) and mechanical (blue) torque (in pu); speed shaft (brown line) and reference speed (red dashed) (in pu)](image)
It can be even seen the intervention of the pitch control system, which commands the feathering of the blades all the times that the speed exceed the reference speed (1.1 in pu).

In this simulation the pitch system is seldom activated because the mean wind speed is 12 m/s, less than the nominal one.

B. Voltage Sag

As told earlier the turbine has a little reactive capability, that essentially depends on the size of the converter. Actually it is rated for 400 kVA, now it must be considered that it has to transfers a maximum active power equal to 194 kW if the turbine reaches the maximum speed (1.283 pu equal to 29 rpm). Thus an amount of 340 kVAr are available for reactive production (included the one consumed by the autotransformer). This value, compared with the nominal active power of the turbine (880 kW), means that the power factor can be regulated 0.95 lag/lead. However the control system is responsive to the voltage variations and so the production of reactive power is function of voltage.

The results presented in Fig. 9 report the behaviour of the generators against a voltage sag of 0.2 pu.

Before the contingency, the voltage at the measurement point of the transformer was within 0.99÷1.01 range and hence the reference of reactive power was zero (as shown in the second diagram). The grid converter had only to supply the reactive power needed by the transformer. At 2 seconds the grid voltage drops at 0.8 pu and the reference of the reactive power reaches its limit, in fact it can be seen in the third diagram that the current in the q-axis, that regulates the production of reactive power, reaches 1 pu.

C. Short Circuit

Afterward the behaviour of the generators during a 25 mΩ impedance short circuit at the point of common coupling (PCC) is analyzed. The aim of this simulation is to study the behaviour of the protection system and of active and reactive powers during a severe voltage drop. The turbines work in the same wind condition seen in the first simulation. Hence the correspondent power production is 713 kW via stator and 58 kW via rotor. The shaft generator speed is 8.2% above synchronism (equivalent to a turbine speed of 23.6 rpm).

Fig. 10 shows, in the first diagram, the grid and the generator voltages, the behaviour of active and reactive powers in the other two diagrams. At the begin of the fault (0.5 s) the power produced by the DFIG stator (brown line) drops to zero because of the voltage collapse. Its reference (red dashed line) instead reaches the maximum value because the generator speeds up. Once the fault is cleared (0.7 s) and until the removal of the crow bar (which has a resistance twenty times the rotor one) the production of active power is function of the slip. When the crow-bar is inserted in fact the generator behaves like a squirrel cage one and because the slip is negative (over-synchronism) the power is produced. If the generator speed were in under-synchronism zone it would adsorb active power from the grid. In any case, as shown in the third diagram, in this period (0.7 s ÷ 1 s) the generator needs reactive power (brown line, third diagram).

Here the reactive control of the grid converter (blue line) takes part to balance the reactive power at the transformer bus (black line).

The wind profile is the same used in the first simulation and, as can be seen in Fig. 11 (blue line), is quite constant because of the short period considered (3 seconds). The following diagram shows the electrical (red line) and the mechanical (blue line) torques at the two ends of the shafts. The electrical torque is a function of the voltage (and of the slip when the rotor is short circuited) and hence it has rapid changes, oppositely to the mechanical one that has slower dynamics. However their difference determines the fast changes in the rotational speed shown in the last diagram.
D. Frequency deviation

In this final paragraph the behaviour of the control system in the case of frequency regulation is analyzed. To make operative this feature the previous grid is substituted with one with smaller short circuit power (5 kA instead of 10, that correspond to 173 MVA) and minor inertia (9 seconds instead of 99). The grid has no primary nor secondary power/frequency regulation, hence the injection of power (after the initialization) by the wind turbines cause an unbalance of the power that the turbines themselves have to adjust.

Fig. 12 shows the increase of the frequency (first diagram) because the power production of the turbines has increased as can be seen in the last diagram. When the frequency reaches 50.3 Hz (1.006 in pu) the control system starts its proportional action and reduces the reference power of the MPT by a coefficient smaller than 1 (second diagram).

The power plant production is so reduced and the frequency deviation is stopped. As there is no integral action the control system will not take the frequency back to 50 Hz.

At last Fig. 13 shows that this power curtailment is managed by the control system by a more intensive pitching of the blades. In fact because the power produced is less than the one available, and hence the accelerating torque is greater than the braking one, the generator speed up and it has to be slowed by reducing the power extract from the wind stream.

V. CONCLUSIONS

The paper addressed an up to date problem related to wind generator contribution to ancillary service provisions. A detailed model of an DFIG wind generator has been presented. The simulations performed by a widely used software code support the DFIG capability to operate in dynamic conditions under voltage sags and short circuits. The dynamic behaviour during frequency deviations is encouraging although more severe conditions should be tested.

REFERENCES