Dynamic Analysis of Grid Connected Wind Farms Using ATP

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Abstract— The use of wind turbines is increasing in very high rates in many countries around the world. Studies to evaluate the impact of connecting these new generation units to the existing power systems must be done and the Alternative Transients Program – ATP, one of the most used simulation tools for power systems transient analysis, does not contain wind generation systems in its libraries. In this paper, three types of variable speed wind generation system models are developed using ATP. The model include the representation of the wind, the turbine mechanical parts, the generator, the static converter, the control systems and the power system. Simulation results of connecting a 10MW wind farm to a real power system are presented.

I. INTRODUCTION

With the increasing concern about the effects of the electrical energy generation processes on the environment, wind energy, which is renewable, clean and available everywhere, is becoming one of the preferred forms for electrical energy production. In European countries, the use of wind turbines is growing approximately 30% each year, contributing strongly to alter the world energetic matrix. Recent technological advances in the fields of power electronics and digital control made possible the use of different arrangements for wind turbines, improving the system efficiency and reducing the price of the wind based electrical energy production plants.

Wind turbines interact with the electrical power system in many ways and for the installation of wind turbines in large scale, special studies are necessary to determine the impact over the system power quality and stability. These studies include the simulation of the wind turbines connected to the power system and the effect of wind speed variation, or disturbances in the wind generation system, in the connection between the wind turbines and the power system or in the power system itself. Some computational tools for static and dynamic analysis of power systems containing wind turbines have been made available recently. However, most of them are expensive slow, require a high computational effort and/or do not encompass the model of some elements of the wind turbine.

Using ATP (Alternative Transients Program) as a dynamic simulation tool for power systems containing wind turbines tends to be well accepted by most power utilities, since the program is free and is already widely used in these companies. In fact, many utilities have already input their power system data in ATP.

In this paper, models including the power system and the mechanical and electrical elements, wind and the control systems of wind turbines using squirrel cage induction generator (SCIG), permanent magnet synchronous generator (PMSG) and doubly fed induction generator (DFIG) are implemented using ATP. The developed algorithms are used to evaluate the behavior of a power system containing a wind farm during the occurrence of typical disturbances in the power system, in the connection system or in the wind farm.

II. SYSTEM MODEL

The wind system model must be accurate enough to allow the correct representation of the phenomena of interest [1]. On the other hand, an over-detailed model could lead to a very high computational effort, which is of course undesirable. The complexity level to be used in modeling the system depends on the objective of the simulations. In this paper, models for transient stability analysis are evaluated. The simulation times are then limited to a few seconds.

The models for wind turbines representation in transient studies must include the electrical components (generator, static converter, power system grid, electrical loads and control systems) and also the mechanical elements (wind speed, torque produced in the rotor axis due to the wind speed, gearbox and pitch angle control).

In this paper, each wind turbine simulated have a rated power of 1MW. The topologies studied are those presented in Fig. 1. The studies consider a wind farm containing 10 wind turbines (10MW) connected to a power system in a point of common coupling having a short circuit power of about 10 times the total wind power installed. The wind farm was represented by an equivalent wind turbine by using the 1 MW turbine per unit parameters and taking the wind farm total power as the base power.
A. Model of the wind

Since the studies presented in this article are related to the power system transient stability behavior, low frequency phenomena of the wind can be neglected. The wind was modeled as [3]:

\[ V_T = V_{\text{const}} + V_R + V_{\sin} \]  

(1)

where \( V_T \) is the wind speed, \( V_{\text{const}} \) represents a constant wind speed component, \( V_R \) is a ramp increasing or decreasing wind speed component and \( V_{\sin} \) is a sinusoidal wind speed.

B. Model of the turbine mechanical elements

The mechanical power transferred from the wind to the aerodynamic rotor is

\[ P = \frac{1}{2} \rho \cdot A \cdot C_p \cdot V_T^3 \]  

(2)

where \( \rho \) is the wind density, \( A \) is the area inside the circle defined by the turbine blades, \( C_p \) is the turbine power coefficient. The input torque in the transmission mechanical system is then

\[ T = \frac{1}{2} \rho \cdot A \cdot C_p \cdot V^3 \]  

(3)

where \( \omega_{\text{rotor}} \) is the aerodynamic rotor speed.

The power coefficient can be expressed in terms of the pitch angle \( \beta \) and the tip speed ratio \( \lambda \) [4]:

\[ C_p(\lambda, \beta) = 0.22 \left( \frac{116}{\lambda_i} - 0.4 \beta - 5 \right) e^{(-12.5) / \lambda_i} \]  

(4)

where \( \lambda_i \) is given by

\[ \frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08 \beta} - \frac{0.35}{\beta^2 + 1} \]

and \( \lambda \) is the tip speed ratio

\[ \lambda = \frac{\omega_{\text{rotor}}}{V} \]  

(5)

The gearbox for the aerodynamic rotor and generator rotor coupling, used in the SCIG and DFIG topologies, was modeled according to Fig. 3. The transmission axis was modeled by considering a spring coefficient \( K_{ms} \) and a damping factor \( c_{ms} \). Further, an ideal transmission system was considered for the angular speed conversion. Equations (6) to (10) were used [5].

\[ \dot{\theta}_{\text{TURBINA}} = \omega_{\text{TURBINA}} \]  

(6)

\[ \dot{\theta}_{\text{h}} = \omega_{\text{TURBINA}} - \frac{\omega_{\text{r}}}{\zeta} \]  

(7)

\[ \omega_{\text{TURBINA}} = \frac{T_{\text{TURBINA}} - T_{\text{CAR}}}{I_{\text{TURBINA}}} \]  

(8)

Fig. 1 Wind turbine topologies studied. (a) Squirrel cage induction generator. (b) Doubly fed induction generator. (c) Permanent magnet synchronous generator.

Fig. 2 ATP diagram of the power system.

The simulations presented in this article were developed using the graphical version of the ATP ATPDraw [2]. The ATP libraries do not include adequate models (ready to use models) to represent the mechanical parts of the wind turbine, the wind and the static converter. These elements, as well as all the control system and the generator were modeled using the tool TACS (Transient Analysis of Control Systems). Only the electrical network was represented using the circuit elements available in the ATP library. Ideal switches were used to represent the static converter, but these switches commands were implemented using TACS.

The simulated system is presented in Fig.2.
where $\theta_k = \theta_{TURBINA} - \frac{\theta_{GL}}{\xi}$ is the angular displacement between the flexible axis ends.

$$T_{CAR} = c_{m3} \left( \omega_{TURBINA} - \frac{\omega_{GI}}{\xi} \right) + K_m \theta_k$$

$$P_t = \omega_{GI} \frac{T_{CAR}}{\xi}$$ (9)

C. Model of the squirrel cage or doubly fed induction generator

Since the objective is to perform transient stability analysis, the induction machine was represented using a fifth order model. Using a reference frame rotating in an arbitrary speed $\omega_a$, the induction machine vector equations are:

$$\vec{v}_s = R_s \vec{i}_s + \hat{\lambda}_s + j\omega_a \vec{\lambda}_s$$ (11)

$$\vec{v}_r = R_r \vec{i}_r + \hat{\lambda}_r + j(\omega_a - \omega_r) \vec{\lambda}_r$$ (12)

$$\frac{2J}{P} \omega_r = T_e - T_l$$ (13)

$$\vec{\lambda}_s = \bar{L}_s \vec{i}_s + L_m \vec{i}_r$$ (14)

$$\vec{\lambda}_r = \bar{L}_m \vec{i}_s + L_r \vec{i}_r$$ (15)

$$T_e = \frac{3}{2} \frac{P}{2} L_m \left( \vec{\lambda}_{rd} i_{sq} - \omega_{r} i_{sd} \right)$$ (16)

In the model above a motor notation was used. Thus, currents entering the stator and rotor windings were considered positive and a positive electromagnetic torque tends to make the rotor speed to increase [6]. Thus, the torque caused by the wind must be considered negative.

D. Model of the permanent magnet synchronous generator

In this case, the space vector model was implemented in a permanent magnet flux oriented reference frame. Once again, a motor notation was used. The model equations are:

$$\begin{align*}
{u}_{sd} &= R_s i_{sd} + \frac{d \psi_{sd}}{dt} + \omega_r \psi_{sq} \\
{u}_{sq} &= R_s i_{sq} + \frac{d \psi_{sq}}{dt} - \omega_r \psi_{sd}
\end{align*}$$ (17)

E. Model of the static converter

The AC/DC/AC converters were represented in the simulation considering ideal switches which command signals were produced with TACS. The grid side converter switches are commanded in such a way to control the DC link voltage and to use the converter as a static reactive condenser. As usual in modern variable speed wind turbines, the machine side converter is controlled to impose the electromagnetic torque that maximizes the power extracted from the wind, limited by the power quality and stability requirements. A more detailed description of the control algorithms is presented in the next section.

III. Control Strategies

A. Grid side converter - GSC

The grid side converters for all three topologies are controlled in the same way. Considering the use of an LCL filter between the grid and the converter, the capacitor phase voltages, converter phase voltages and input inductors voltages are related by the equation

$$\begin{bmatrix}
{v}_A \\
{v}_B \\
{v}_C
\end{bmatrix} = R \begin{bmatrix}
i_A \\
i_B \\
i_C
\end{bmatrix} + L \frac{d}{dt} \begin{bmatrix}
i_A \\
i_B \\
i_C
\end{bmatrix}$$ (20)

Considering that, due to the connection used in the step up transformer, there is no zero sequence component, then (20) can be expressed in an arbitrary dq reference frame as:

$$\vec{v}_{cap} - \vec{v}_{conv} = R\vec{i} + L \frac{d}{dt} \vec{i} + j\omega_a L \vec{i}$$ (21)

The GSC switches are commanded to control the real and reactive power fluxes between the grid and the converter. Using a dq reference frame oriented by the filter capacitor voltage, the instantaneous active and reactive power components delivered to the GSC are:

$$P = \frac{3}{2} v_{d(cap)} i_d$$ (22)

$$Q = \frac{3}{2} v_{d(cap)} i_q$$ (23)

Neglecting the converter losses, the difference between the active power delivered by the generator to the machine side converter and the power injected in the grid by the grid side converter is stored in the DC link capacitor. Thus, the reference value of the real power to be delivered to the power
system (or the d axis current component) is the DC link voltage controller output. It is important to notice that imposing a fixed value for the DC link voltage means that all the generated power is instantaneously injected in the grid. In this case, wind speed variations may cause voltage fluctuations due to the injected real power oscillations. Admitting some fluctuation in the DC link voltage can be used to reduce grid voltage oscillations caused by transients in the generated power.

Due to the wind typical variations, most of the time the GSC rated power is not fully used. This makes possible to use the converter available capability as a static VAR condenser. The q axis current component is used to control the reactive power flow between the grid and the GSC.

The GSC voltage vector necessary for the DC link voltage and reactive power control is produced by using a vector or PWM scheme.

Fig. 4 presents the GSC control in a block diagram form.

B. Machine side converter - MSC

In variable speed wind turbines, a scheme to track the maximum power coefficient (Cp) can be used. According to (4), for each wind speed, there is a rotor angular speed that allows the maximum power to be extracted. In order to track the maximum power coefficient, the $C_p(\lambda, \beta)$ curves are used to determine the optimum tip speed ratio for the measured wind speed and then calculate the optimum rotor angular speed:

$$\omega_r^{OPT} = \frac{\lambda^{OPT} V}{R} \quad (24)$$

A control speed scheme can then be used for imposing the optimal rotor angular speed. In the scheme presented in this paper, vector control strategies were used for the rotor speed control. The MSC control schemes for the three topologies studied in this paper are very similar and are presented in Fig. 5, which includes a table with the different feedforward compensation terms.

![Fig. 4 – GSC control block diagram.](image)

![Fig. 5 – Block diagram of the MSC control.](image)

![Fig. 6 – Pitch angle control.](image)

C. Pitch angle control

When the wind speed is low, it is desirable to maintain the pitch angle $\beta$ in a value such that the wind power converted into mechanical form is maximum. By doing this and controlling the rotor angular speed to maximize the power coefficient $C_p$ allow maximum power extraction from the wind. However, when the wind speed is above the rated value, operation with maximum power extraction could cause electrical and mechanical problems to the generator and turbine. In this case, the pitch angle can be controlled in order to reduce the power coefficient and maintain the mechanical power absorbed in the rated value. Fig. 6 shows the block diagram for the pitch angle control. $P_{ref}$ is the turbine rated power (a negative value is used, since the motor notation used makes the generated power to be negative). Thus, if the wind speed is not too high, the absolute value of the generated power is smaller than the absolute value of $P_{ref}$. The error is then a negative value and the PI controller, which is the pitch angle reference value, output tend to saturate in the minimum value (set to zero), allowing maximum power extraction. If the wind speed increases above the rated value, the PI controller input becomes positive and a positive pitch angle command will result. A servo drive is then used to position the turbine blades in the correct pitch angle.

IV. RESULTS

The developed simulation algorithms were used to evaluate the system behavior during critical situations, when disturbances in the wind speed, in the wind farm and in the power system occur.

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A. Wind speed disturbances

The wind speed disturbance was represented by a sinusoidal wind speed superimposed by an increasing ramp (10 m/s to 12 m/s), followed by a constant speed and a then decreasing ramp. In order to show the results of the three topologies in the same figure, the PMSG rotor speed (which is much lower because the gearbox is not used) was multiplied by 125. Using the wind speed profiles, the optimum rotor speed, for maximum power point tracking (MPPT) was plotted. Figs. 7 and 8 present the optimum and actual rotor speeds (in electrical radians per second), the DC link voltage and the line voltages in point of common coupling (PCC) for the three topologies. As seen, it is possible to achieve MPPT in the three strategies without causing inadmissible voltage oscillations for the wind disturbance considered. However, in the PMSG turbine simulated, the DC link voltage does not follow the reference during the wind speed descending ramp. In order to follow the descending rotor speed reference, the speed controller tends to make the electromagnetic torque (and the generated real power) to increase. The rise in the DC link voltage means that the increment of generated power is not being completely delivered to the grid. The control parameters of the DC link voltage must be reviewed to allow a faster energy transference to the grid, but this faster transferece might cause stronger voltage oscillations in the PCC. If inadmissible voltage oscillations in the PCC have occurred, then some strategy should be used to limit the generated active power. In this case, the maximum power point could not be tracked.

B. Disturbances in the wind farm

As an example of disturbance in the wind farm the loss of one of the transmission lines connecting the farm to the power system was considered. Fig. 9 presents the machine speed control for MPPT and the DC link voltage. These quantities are not severely affected by the contingency. This fact was expected since a constant power generation is commanded. Fig. 10 shows the current in the remaining line. Of course, the line must be capable of conducting such current. The results show that no stability problem arises with the disturbance.

C. Disturbances in the power system

In order to evaluate the effect of disturbances in the power system over the wind farm, a three-phase fault in the power system that causes a voltage sag of approximately 50% in the PCC, with a duration of 200 ms, as shown in Fig. 11, was taken as an example. Fig. 12 shows the machine speed control for MPPT and the DC link voltage. In the SCIG and PMSG topologies, that use a converter for the connection of the generator stator and the power system, the DC link voltage rises during the disturbance. This occurs due to the current limitations of the GSC. Since the power system voltage is reduced, the maximum power that can be transferred through GSC is also reduced and the generated power that exceeds this limited value is stored in the DC link capacitors. This does not occur in the DFIG topology, because most of the power is transferred to the grid through the stator, which is directly connected to the power system.
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V. CONCLUSION
The results presented in this paper show the adequacy of ATPDraw to accomplish the studies necessary to evaluate the impact of connecting wind farms to power systems, since the elements of the wind farm are adequately modeled. The simulations presented show the possibility to evaluate the consequences of the possible disturbances, as well as to deduce the solutions and verify their use. Further, the developed tool allow the investigation of applying control strategies to the converters taking into consideration the power quality.