DYNAMIC MODELING OF WIND TURBINES FOR SYSTEM FREQUENCY CONTROL

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Abstract This paper presents a control strategy for a grid connected doubly fed induction generator (DFIG)-based wind energy conversion system (WECS). Control strategies for the grid side and rotor side placed in the rotor circuit of the Doubly Fed Induction Generator (DFIG) are presented along with the mathematical modeling of the Wind Energy Conversion System. In this control approach, wind generators operate according to a deloaded optimum power extraction curve such that the active power provided by each wind turbine increases or decreases during system frequency changes. The control strategy defined at the wind generator to supply primary frequency regulation capability exploits a combination of control of the static converters and pitch control, adjusting the rotor speed and the active power according to the deloaded optimum power extraction curve. The results are obtained at different speed and operating condition.

Keywords – Dynamic Model, Wind Turbine, Frequency Control, DFIG

I. INTRODUCTION

Frequency control is essential for a secure and stable operation of any power system. Nowadays, power systems are facing a large wind penetration increase that may lead to difficulties in frequency control. It is recognized that the presence of a large wind power penetration (either as embedded generation or in large wind parks) may lead to a reduction of power system frequency regulation capabilities, namely, when wind generation replaces conventional synchronous units that supply the major portion of the active power consumed by the grid and are responsible for re-establishing the overall system frequency.

Wind energy is non-polluting character and plenty of availability has made wind energy as a major research area for power engineers. The increasingly wide spread use of wind generation power networks translates into a higher participation of this technology in the total generation mix in countries where the penetration of wind energy conversion system is already significant system operators are beginning to worry about the performance of the primary frequency regulation system, since those units do not currently co-operate to keep the frequency under control while the number of units capable of doing so is decreasing in relative terms. Accordingly the need to study the way in which wind units could participate in system frequencies support strongly arises. In spite increasing penetration of wind turbines into the power grid, the frequency regulation and AGC tasks are mainly under taken by conventional generation units. The goal of frequency regulation and AGC is to keep frequency within frequency specified limits through primary and secondary control of Governor. Accordingly, it has become necessary to model the complete wind energy systems in order to study their impact and also to study wind power plant control. Even Grid codes are being revised to ensure that wind turbines would contribute to the control of voltage and frequency and also to stay connected to the host network following a disturbance. So wind turbine participation in system frequency regulation is an expected important development and it is the motivation for my paper. In this paper, for the purpose of analysis two control techniques have been proposed.

II. OVERVIEW OF WIND TURBINE GENERATOR

Wind Turbine is a device for conversion of kinetic energy of the wind to electricity. The transformation to mechanical torque is done by aero dynamical forces acting on the rotor blades. The wind turbine shaft then transports the power to the generator which is connected to the electrical grid. Usually there is a gear box between the slowly rotating turbine shaft and the more rapidly rotating generator shaft. So, turbine blades can’t extract all kinetic energy from the wind. The following equation represents the total wind power $P_{wind}$:

$$P_{wind} = \frac{1}{2} \rho \pi R^2 V_{wind}^3 \quad (1)$$

Where,
- $\rho$ – Air Density ($kg/m^3$) = 1.225 $kg/m^3$
- $R$ – Rotor Radius (m)
- $V_{wind}$ – Wind speed (m/s)

The relationship between the total wind power, $P_{wind}$ and mechanical power $P_{mech}$ in the following equation:

$$P_{mech} = C_p \cdot P_{wind} \quad (2)$$

According to the Betz’s limit, theoretically, the mechanical power $P_{mech}$ can be extract nearly 59% of
the kinetic energy of the wind. Practically the optimal value of \( C_p \) lies between 0.52 – 0.55. The mechanical power obtained is

\[
P_{\text{mech}} = C_p \cdot \frac{1}{2} \cdot \rho_{\text{air}} \cdot \pi \cdot R^2 \cdot V_{\text{wind}}^3
\]  

(3)

The relationship between power and Torque of wind turbine is

\[
P_{\text{mech}} = T_{\text{mech}} \cdot \omega_{\text{turb}}
\]  

(4)

Where, \( \omega_{\text{turb}} \) = Rotational Speed of the Turbine.

From the above equation it is clear that \( P_{\text{mech}} \) depends on rotational speed \( \omega_{\text{turb}} \), the wind speed \( V_{\text{wind}} \) and on the turbine blade angle (\( \beta \)). Further, in the aerodynamics of the wind turbine, the tip speed ratio is commonly used and it is defined as the ratio of the rotor blade tip speed \( (V_{\text{tip}} = W_{\text{turb}} \cdot \omega) \) and the wind speed \( (V_{\text{wind}}) \)

\[
\lambda = \frac{V_{\text{tip}}}{V_{\text{wind}}} = \frac{W_{\text{turb}} \cdot \omega}{V_{\text{wind}}}
\]  

(5)

\( R \) = Rotor Radius of turbine blades (measured in meters) and \( W_{\text{turb}} \) is measured in (rad/s). The power efficiency coefficient, \( C_p \) value of the blades is depend on the blade angle \( \beta \), and the tip speed ratio \( \lambda \). So, \( C_p \) is the function of \( \lambda \) and \( \beta \) and can be expressed in the following way. Now \( P_{\text{mech}} \) can be described in the following way.

\[
P_{\text{mech}} = \frac{1}{2} \cdot \rho_{\text{air}} \cdot \pi \cdot R^2 \cdot V_{\text{wind}}^3 \cdot C_p (\lambda, \beta)
\]  

(6)

If the \( C_p - \lambda \) curve is known for a specific wind turbine it is easy to construct the curve of \( C_p \) against rotational speed for any wind speed \( V_{\text{wind}} \). For specific wind speed the optimal operational point of the wind turbine can be determined by tracking the rotor speed to the optimal tip speed ratio, \( \lambda_{\text{opt}} \). Based on \( \lambda_{\text{opt}} \) rotational speed \( W_{\text{turb - opt}} \) can also be known by the following equation.

\[
W_{\text{turb-opt}} = \frac{\lambda_{\text{opt}} \cdot V_{\text{wind}}}{R}
\]  

(7)

For the fixed speed wind turbines it have to designed in order for the rotational speed to match the most likely wind speed in the area of installation and for variable speed wind turbines, the rotational speed of the wind turbine is adjusted over a wide range of wind speeds so that the tip speed ratio \( \lambda \) is maintained at optimal tip speed ratio \( \lambda_{\text{opt}} \). Thereby, the power efficiency coefficient, \( C_p \) reaches its maximum value and as a result, the mechanical power, \( P_{\text{mech}} \) output of a variable speed wind turbine will be higher than that of a similar fixed speed wind turbine over a wider range of wind speeds. At higher wind speeds the mechanical power is kept at the rated level of the wind turbine by controlling the pitch of the turbine blades.

### III. OUTLINE OF CONTROL SCHEMES

Two types of control using Doubly Fed Induction Generator (DFIG) can be adopted to provide contributions for system frequency control:

- a) Inertial control;
- b) Primary frequency control.

Inertia control can be provided in a DFIWG through a supplementary inertia control loop, to reintroduce inertia response. The proposed method exploits the kinetic energy stored in the rotating mass of wind turbines, such that the additional amount of power supplied by the wind generator to the grid is proportional to the derivative of the system frequency (df/sys/dt). Nevertheless, the inertia control can be similar to the one usually used in the synchronous generator. In this case, the droop loop (characterized by a regulation \( R \)) is used to produce a change in the active power injected by the wind generator being proportional to the difference between the measured and the nominal system frequency. Both frequency control schemes, described before, are exploited such that the droop loop is only activated when the grid frequency exceeds/falls from the nominal value. And also it should be activated only for a short period of time, if is activated for long time the system may become unstable. A limit on the Wind Turbine speeds should be taken within the threshold of cut out speed and also energy extraction from DFIG machine will be permitted only when the mechanical speeds lay within the cut out speeds(0.8-1.2pu).When exploiting an inertia control mode, the wind generator is, however, unable to participate effectively in the grid primary frequency regulation because it is not deloaded, i.e., there is not a margin for its output active power increase during large low-frequency periods.

A primary frequency control strategy will be developed, such that the DFIWG is able to provide a proportional frequency response, in terms of grid injected active power, exploiting a pitch angle controller. In this case, the active power injected by the wind generator is adjusted through the regulation of the minimum pitch angle according to frequency variation. The implementation of more sophisticated control schemes, seeking to control the rotational speed of the rotor, to improve the dynamic control in order to adjust the mechanical power. This electrical power injection is defined from a proportional frequency regulation loop together with a power reference adjustment obtained from a deloaded power curve, such that a new equilibrium can be obtained when frequency changes occur. In this way, active power injected by the machine is kept on, while frequency deviation stands, therefore contributing for system primary frequency control. This approach (that includes a proportional integral control for pitch angle control) avoids the use of a mechanical characteristics
look-up table, usually needed to identify the required pitch angle and reference speed that would lead to the required response.

The pitch control is also responsible for limiting the mechanical power of the wind turbine during high wind speeds.

IV. ASSUMPTIONS IN PARTICIPATION OF DFIG IN FREQUENCY REGULATION:

First assumption made is that the mechanical power of DFIG based wind turbine is constant since wind speed is taken to be constant and therefore uncertainty of wind power has not been considered.

Second assumption is that in the power system with mixed generation (Conventional +Wind), conventional generation is able to supply the additional demand during the disturbances and increase the production as needed for whole time disturbance persists.

V. DYNAMIC MODEL OF WIND ENERGY CONVERSION SYSTEM

The following block diagram (Fig: 1) represents the Dynamic model of wind turbine. The main purposes of the turbine control are to maximize production by maintaining the desired rotor speed and avoiding equipments overloads. Blade pitch control and electrical Control are two main controls to satisfy the objective.

Generator/Converer Model: This model represents the physical equivalent of the generator and converter hardware and provides the interface between the WTG electrical controller and network.

Electrical Control Model: This model indicates the active and reactive power to be delivered to the power system based on input from the turbine model and power systems conditions.

VI. WIND TURBINE AND TURBINE CONTROL MODEL:

Wind turbine model provides a simplified representation of a very complex electro–mechanical system. The model represents the all controls and mechanical dynamics of the wind turbine.

VII. DYNAMIC MODEL OF POWER SYSTEM WITH WTG

In Fig: 2 shown below, a classical model for Frequency regulation studies shown. The box named Conventional Generation has the power reference as input and the generated power as output. This box models the dynamics of an equivalent machine of a system with different kinds of generation technologies (hydro, gas, steam turbine etc.) along with its governor. The total system active power demand (P_L) is subtracted from the generated power (P_G) while the total power interchanged with neighbor systems (P_T) is added. In order to take into account the wind generation, a new term defined as (P_{NC}) is added. In steady state, the total power balance is then follows

\[ P_G + P_T + P_{NC} - P_L = P_A = 0 \]  \hspace{1cm} (8)

The term P_C stands for the secondary control or AGC power reference and P_P stands for primary control.
Wind Turbine Gust Model

Emulating Inertial Response

In normal operation, the controllers of DFIG try to keep the turbine at its optimal speed in order to produce maximum power. To emulate the inertial response, the power controller is adapted which is represented by the equation shown below. In this controller additional set point to simulate the inertial response is added. This set point is a function of the change in frequency.

$$\Delta P_{inertial} = \frac{-T_{1s}}{1 + s T_{2}} \cdot \Delta f$$

(9)

Where $\Delta f$ is the change in system frequency after disturbances, $T_1$ and $T_2$ are the inertial controller parameters. The controller will react on the rate of change of frequency $\left(\frac{d\Delta f}{dx}\right)$.

VIII. DROOP CONTROL (PRIMARY FREQUENCY CONTROL)

The additional power reference of the droop controller is proportional to the deviation of the frequency from the nominal value. If the additional power signal for delivering frequency control is denoted by $\Delta P_{freq}$ then the signal will be having two components. A first component $\Delta P_{inertial}$ is proportional to the rate of change of frequency and the second component, $\Delta P_{droop}$ is proportional to the deviation of the frequency.

$$\Delta P_{freq} = \frac{-T_{1s}}{1 + s T_{2}} \cdot \Delta f + \frac{-1}{R} \Delta f$$

(10)

Different controllers are added to participate in the inertial and primary frequency control.

Implementation of Control Scheme

Frequency variations can be controlled using inertial and droop controllers.

If for example, the frequency suddenly drops, the inertial controller is activated and delivers an additional power reference input to the converter of Doubly Fed Induction Generator. The denominator of the inertial controller is a low pass filter. Hence, the controller does not react to small frequency variations. During disturbances, the Doubly Fed Induction Generator increases/decreases its power output to arrest the drop/surge in frequency and improves significantly the system performance. Due to the release of its kinetic energy, not only the minimum frequency improved but also the rate of change of frequency is also improved. In contrast with the benefits, some disadvantages remain with inertia power output or primary control. However, in practice, the maximum achievable inertial response is restricted by current limits and mechanical constraints. The rotor speed starts to fall as the electrical power raises and due to imbalance between mechanical power coming from wind (Constant wind speed assumed) and increase in electrical power. When the electrical power settles with the pre-disturbances value, the turbine accelerates back to its optimal rotor speed.

Variation of Control Parameters

The control parameters can be varied to give the optimal frequency performance in a grid consisting of different generators with different governor characteristics (Example fast/slow governor and low/high inertia). The first parameter ($T_1$) determines the gain by which the rate of change in frequency is converted into power reference. When $T_2$ is increased, the rate of change is filtered out. The controller observes actually a low rate of change of frequency in that case, therefore provides a smaller and delayed inertial response. That means short term active power support by wind turbine is less and also has got a negative influence on minimum frequency and rate of change of frequency. High values of $T_1$ and low values of $T_2$ will give good frequency response.

Droop control will also be integrated in the model. Wind turbine is contributing to frequency control by releasing or absorbing kinetic energy. Droop control can be activated for a short period of time. If the droop controller remains activated for a long time in the case of a frequency dip, the decrease in speed will be more and the system sometimes may go unstable.

Mathematical Design of DFIG

A simplified mathematical model will be helpful in efficient analysis of the behaviour of any complex system, under different operating conditions and control strategies. For a DFIG, the most common way of deriving a mathematical model is in terms of direct and quadrature axes quantities in a frame which rotates synchronously with stator flux vector. An equivalent circuit is shown below.

$$v_{dq} = r_i i_{dq} + j m \Psi_{dqs} + \frac{d}{dt} \left(\frac{d}{d\theta} \Psi_{dqs}\right)$$

(11)
The complex torque equation of (15) can be resolved in reference d-q leading to

$$T_e = \frac{3}{2} R_s \left[ \Psi_{qs} \cdot i_{qs} \right] = -\frac{3}{2} R_s \left[ \Psi_{qd} \cdot i_{qd} \right]$$

The stator side active and reactive powers are given as

$$P_s = \frac{3}{2} R_s \left[ \Psi_{qs} \cdot i_{qs} \right] = \frac{3}{2} \left( v_{dq}^T i_{dq} + v_{ds}^T i_{ds} \right)$$

$$Q_s = \frac{3}{2} \text{Im} \left[ \Psi_{qs} \cdot i_{qs} \right] = \frac{3}{2} \left( v_{dq}^T i_{dq} - v_{ds}^T i_{ds} \right)$$

Considering that

$$I_{qs} = \frac{1}{L_s} \Psi_{qs} - \frac{L_m}{L_s} i_{qd}$$

The active and reactive power equations are modified as

$$P_s = \frac{3}{2} \frac{1}{L_s} \left( v_{dq}^T \Psi_{dq} - v_{ds}^T \Psi_{ds} \right) - \frac{L_m}{L_s} \left( v_{dq}^T i_{dq} + v_{ds}^T i_{ds} \right)$$

$$Q_s = \frac{3}{2} \frac{1}{L_s} \left( v_{dq}^T \Psi_{dq} - v_{ds}^T \Psi_{ds} \right) + \frac{L_m}{L_s} \left( v_{dq}^T i_{dq} + v_{ds}^T i_{ds} \right)$$

Thus, the magnitudes of stator currents govern the active and reactive powers of the stator, and these currents depend on the rotor currents. Thus, the active and reactive power can be controlled by appropriately controlling the rotor currents ($i_{dq}$ and $i_{ds}$) in WECS.

**CONCLUSION**

Traditionally, frequency regulation in power system will be taken care by conventional generators. With further growth of wind energy in power systems, power system operators are demanding more and more participation of wind turbine in the ancillary services especially frequency regulation. With proposed control, the Doubly Fed Induction Generator is able to support the conventional generator in regulating frequency. Because Doubly Fed Induction Generator can power with different mechanical speed and it has got the ability to instantly reduce the speed by converting the stored mechanical energy to apparent power.

Change in frequency oscillations are controlled more efficiently with proposed control when PI controller of Speed regulator is tuned. The extraction of energy from DFIG will be co-ordinate with conventional generates which as result, damping overshoot and frequency can be improved significantly. In order to optimize the use of DFIG machine and their performance in participation of frequency regulation with that of conventional generators in power systems better optimization techniques can also be used.

**REFERENCES**


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