

Review of Inertial Control Methods for DFIG-Based Wind Turbines

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Abstract—Due to the fact the control system of DFIG is not based on the power system frequency, the whole inertia of the power system is reducing rapidly with the penetration of wind generation increasing. This is extremely bad for the stability of the system frequency. The capability of doubly fed induction generator (DFIG) to participate in the primary frequency regulation is discussed in this paper. This paper reviews some studies about the inertia control and droop control for DFIG-based wind turbine.

Index Terms—doubly fed induction generator, inertia control, droop control, maximum power point tracking

I. INTRODUCTION

The world-wide concern about the environment has led to increasing interest in technologies for generation of renewable electrical energy. One way of generating electricity from renewable sources is to use wind turbines. However, with the increasing percentage of wind energy into the network, new challenges with regards to the functioning of the current power system are emerging. Reference [1] presents some of the issues being encountered in the system frequency regulation function when the penetration level of wind energy in the electric grid increases considerably. 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. Reference [2] proposes a control scheme that allows DFIGs to participate effectively in system frequency regulation. Reference [3] presents a review on the various strategies for frequency regulation used in wind energy conversion system. The capability of two wind turbines, doubly fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG) to participate in the primary frequency regulation and offer primary reserve is discussed in [3].

Most of the wind turbines that are used nowadays are DFIGs. The traditional power control system and dynamic model of DFIG-based wind turbines are described in [4], [5]. In the case of variable-speed constant-frequency generators such as DFIG and

converter-coupled multi-pole synchronous generators, rotor mechanical speed is decoupled from system speed. As the speed (or torque) only varies if the reference set-point obtained from the MPT changes due to varying wind speed, this is a consequence of very fast regulation of electrical torque by the rotor side converter (RSC) according to a maximum power tracking (MPT) algorithm. It is undesirable when there are a large number of DFIG wind turbines operating, especially in periods of low load and on smaller power systems (e.g., Great Britain and Ireland). A lower system inertia will result in larger and faster frequency deviations after occurrence of abrupt variations in generation and load [6]. Therefore, ancillary inertia control strategies of DFIG need to be developed to compensate for this deficiency. It is proved that DFIG-based wind turbines potentially can provide inertial response, just like synchronous plants [7]. Reference [8] proposed a method to let variable-speed wind turbines emulate inertia. In this paper, a variable virtual inertia of DFIG is emulated and some inertia control strategies which make the “hidden inertia” available to the grid are introduced.

II. WIND TURBINE INERTIA

The power that wind turbine can recover can be expressed by:

$$P_i = (1/2)\rho V_w^3 \pi R_{rotor}^2 C_p \quad (1)$$

where ρ is the air density, V_w is the wind speed, R_{rotor} is the radius of the turbine rotor and C_p is the power coefficient. The kinetic energy stored in the rotating mass of a synchronous generator (E_k) can be expressed as:

$$E_k = \frac{1}{2} J_r \omega_m^2 \quad (2)$$

where J_r is the inertia of the rotor and ω_m is the present wind turbine rotor speed. Generally, the inertia constant of a synchronous generator (H) is defined as the ratio of the total stored energy at the nominal speed ω_{mN} to the rated apparent power S_n :

$$H = \frac{E_k}{S_n} = \frac{J_r \omega_{mN}^2}{2S_n} \quad (3)$$

where J_r is the moment of inertia in the shaft. The relationship between the nominal rotor speed (ω_{mN}) and the grid synchronous angular speed (ω_e) in the synchronous generator is:

$$\omega_e = p\omega_{mN} \quad (4)$$

where p is the number of pole pairs in synchronous generator. Hence, the inertia constant of the power system with DFIG-based wind farms (H_{wt}) can be expressed as:

$$H_{wt} = \frac{\sum_{i=1}^n \left(\frac{1}{2p_i^2} J_{r,i} \omega_e^2 \right) + \sum_{j=1}^m E_{k_DFIG,j}}{S_{N_wt}} \quad (5)$$

where p_i and $J_{r,i}$ is the number of pole pairs and moment of inertia for synchronous generator i respectively. S_{N_wt} is the nominal capacity of the grid, and $E_{k_DFIG,j}$ is the kinetic energy stored in the rotating mass of DFIG-based wind turbine j . The kinetic energy stored in the rotating mass of a synchronous generator can be expressed as:

$$E_{k_DFIG} = \int (P_t - P_m) dt = \frac{1}{2} J_r \omega_m^2 \quad (6)$$

The relation between the input mechanical power (P_t) and the output electrical power (P_m) is described by:

$$\begin{aligned} P_t - P_m &= \frac{dE_{k_DFIG}}{dt} = \frac{d}{dt} \left(\frac{1}{2} J_r \omega_m^2 \right) = J_r \omega_m \frac{d\omega_m}{dt} \\ &= J_r \frac{\omega_m}{\omega_e} \frac{d\omega_m}{d\omega_e} \omega_e \frac{d\omega_e}{dt} = J_v \omega_e \frac{d\omega_e}{dt} \end{aligned} \quad (7)$$

From (6), (7):

$$E_{k_DFIG} = \frac{1}{2} J_v \omega_e^2 \quad (8)$$

where J_r is the constant inertia of DFIG, J_v is the virtual inertia of DFIG. As the traditional DFIG control system decouples the mechanical and electrical systems, which means $d\omega_m/d\omega_e = 0$, $E_{k_DFIG,j}$ can not be seen if maximum power point tracking (MPPT) control is used:

$$\sum_{j=1}^m E_{k_DFIG,j} \approx 0 \quad (9)$$

The inertia constant of the DFIG (H_D) can be defined as:

$$H_D = \frac{E_{k_DFIG}}{S_D} = \frac{J_v \omega_e^2}{2p^2 S_D} \quad (10)$$

where S_D is the nominal apparent power of DFIG.

$$H_{wt} = \frac{\sum_{i=1}^n \left(\frac{1}{2p_i^2} J_{r,i} \omega_e^2 \right) + \sum_{j=1}^m \left(\frac{1}{2p_j^2 S_D} J_{v,j} \omega_e^2 \right)}{S_{N_wt}} \quad (11)$$

III. INERTIA CONTROL METHOD

Recently, several inertial strategies have been proposed to give DFIG an inertia response. With inertial response

is meant that the wind turbine will increase its power supplied to the grid, during a drop in the grid frequency. The comparison of the inertia response of fixed-speed induction generator and DFIG with proposed control system which has been introduced above is discussed in [9]. There are three inertia control strategies have been introduced in this section: adding frequency deviation loops inertia control method, the switch of power tracing curves method and using a super-capacitor method.

A. Adding Frequency Deviation Loops Inertia Control Method

Reference [8] adds an additional controller to adapt the power set point as a function of the deviation of the grid frequency to give variable speed wind turbines an inertial response is shown in Fig. 1.

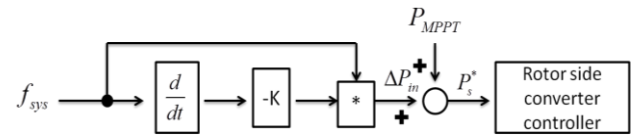


Figure 1. Inertia control.

where P_{MPPT} is the reference for the MPPT control, and ΔP_m is similar to the difference between the mechanical and electromagnetic active power. From Fig. 1, the inertial power generated by inertial control for inertial control is expressed as:

$$P_t - P_m = \Delta P_m = K \bar{f}_{sys} \frac{d\bar{f}_{sys}}{dt} = K \bar{\omega}_s \frac{d\bar{\omega}_s}{dt} \quad (12)$$

where \bar{f}_{sys} is the per-unit system frequency. $\bar{\omega}_s$ is the present per-unit synchronous generator speed and K is the Inertial controller gain, it is analogous to the equivalent moment of inertia.

To provide an appropriate primary inertial support to the system, the calculation of K is a crucial problem. In the traditional approach, K is regarded as twice the total inertia constant (H_{wt}) of wind energy conversion system (WECS), that is, $K = 2H_{wt}$ [10]. The reason is that K represents the ratio between the torque difference and changing rate of synchronous generator speed ($d\omega_e/dt$), whereas H represents the ratio between the torque difference and changing rate of wind turbine rotor speed ($d\omega_m/dt$). Therefore the method in [10] is just an approximation and the frequency may not be well controlled to some extent. Reference [11] gives a better estimation for the gain of inertial control (K) through trial and error.

Reference [12] proposes an idea to obtain K from the standpoint of wind turbine stability and frequency security. From the point of view of energy balance, the kinetic energy is gained by the integral of both sides of (12):

$$\bar{E}_k = \frac{K}{2} (\bar{\omega}_s^2 - \bar{\omega}_{s0}^2) \quad (13)$$

where $\bar{\omega}_{s0}$ is the initial per-unit synchronous generator speed. From (3), (7):

$$\bar{E}_k = H \frac{\omega_m^2 - \omega_{m0}^2}{\omega_{mN}^2} = H \frac{\omega_{sN}^2}{\omega_{mN}^2} \frac{\omega_m^2 - \omega_{m0}^2}{\omega_{sN}^2} \quad (14)$$

where ω_m and ω_{m0} are the present and initial rotor speed. ω_{sN} is the rated synchronous speed. Then:

$$K = 2H_{total} \frac{\omega_{sN}^2}{\omega_{mN}^2} \frac{\omega_m^2 - \omega_{m0}^2}{\omega_s^2 - \omega_{s0}^2} \quad (15)$$

where $\bar{\omega}_m$ is the per-unit rotor speed with ω_{sN} as base value. $\bar{\omega}_{m0}$ is the initial per-unit rotor speed with ω_{sN} as base value.

B. The Switch of Power Tracing Curves

The other method of inertia control for DFIG is the switch of power tracing curves. The idea behind this method is to change the k_{opt} of power tracing curve when the frequency begins disturbing. As a result the output power of DFIG-based wind turbine is able to response to the system frequency change. Where:

$$k_{opt} = \frac{1}{2} \frac{R_{rotor}^2 \pi \rho V_w^3 C_p}{\omega_m^3} \quad (16)$$

The virtual inertia control strategy based on shifting power tracking curves of the DFIG is proposed in [13], [14]. It has three components: wash out unit, change of k_{opt} unit and power tracing curves unit in Fig. 2. In addition, the value of k_{opt} is restricted in the range from k_{min} to k_{max} . Assuming that the wind velocity and the mechanical power of the DFIG remain constant:

$$P_t = k_{opt} \omega_m^3 \approx k_{opt}^* (\omega_m + \Delta\omega_m)^3 \quad (17)$$

From (17), the formula used to evaluate the value of k_{opt}^* can be expressed as follows:

$$k_{opt}^* \approx \frac{\omega_m^3}{(\omega_m + \Delta\omega_m)^3} k_{opt} \quad (18)$$

After the optimization of k_{opt}^* is complete, DFIG will operate on a new power tracing curve. The reference output power P_{opt}^* becomes different from before. The scheme of this method is displayed in Fig. 2.

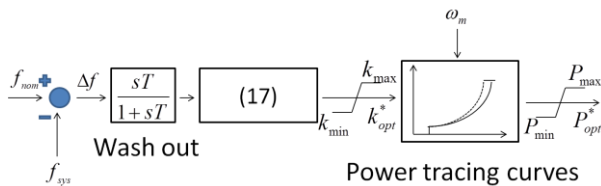


Figure 2. Scheme for switch of power tracing curves.

Adding frequency-power loops inertia control method and the switch of power tracing curves method have been introduced above. The difference between adding frequency deviation loops method and switch of power tracing curves method for inertia control of DFIG have been discussed in [15].

C. Using a Super-Capacitor Method

The other way to implement virtual inertia is to use a super-capacitor connected to the DC link of the back-to-back inverter controlling the DFIG. The virtual inertia control strategy based on super-capacitor is described in [16]. A wind power generator is shown in Fig. 3.

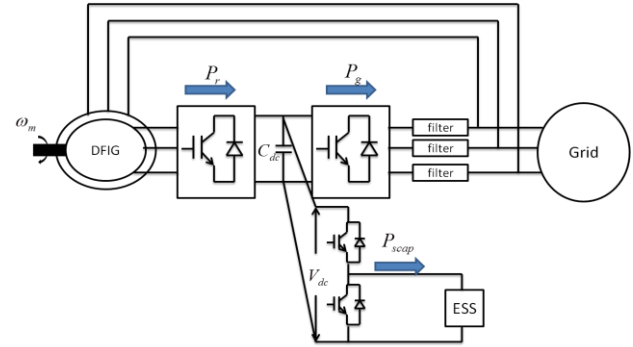


Figure 3. Wind power generator.

The super-capacitor shown in Fig. 3 will be responsible for mimicking the rotating mass behavior. From Fig. 3, the relation between V_{dc} , the DC-link capacitor voltage; P_g , grid side converter (GSC) output power; P_r , RSC needed power; and P_{scap} , the power absorbed by the super-capacitor is presented:

$$P_r - P_g - P_{scap} = \frac{1}{2} C_{dc} \frac{dV_{dc}^2}{dt} \quad (19)$$

Since GSC should maintain a constant DC link voltage, the derivative term will be zero in steady-state. This equation can be expressed by:

$$P_g = P_r - P_{scap} \quad (20)$$

The inertia relation in machines, introduced by (7), can be simplified as (21):

$$P_m = P_t - J_r \omega_m \frac{d\omega_m}{dt} \quad (21)$$

To implement virtual inertia in the GSC controller, P_m should be replaced by P_g , which is the output power of GSC and P_t should be replaced by P_r , which is the power extracted from the rotor terminals of DFIG. Since virtual inertia emulated by this method does not participate in power sharing, no mass energy storage device is needed. This finding leads to economic advantages: either the rotating mass connected to the DFIG shaft or a super-capacitor connected via a DC/DC converter to a back-to-back inverter DC-link could be used.

IV. DROOP CONTROL

Nowadays, the grid frequency is controlled by the conventional power plants. The droop controller regulates the active power output in proportion to the frequency change with the ratio of $1/R$ so as to coordinate the wind plant with existing synchronous machine and DFIG governors to share the change in load. Reference [17]

presents torque- and power-droop implementations in DFIG-based units by some simple modifications in the conventional control. The DFIG droop characteristic shown in Fig. 4 is considered the same as that of a synchronous machine.

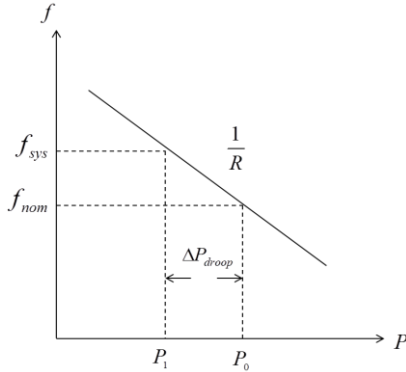


Figure 4. DFIG droop characteristic.

where R is droop gain. f_{sys} and f_{nom} are the present system frequency and nominal system frequency. P_1 and P_0 are the active power corresponding to f_{sys} and f_{nom} , respectively. From Fig. 4, the additional active power shown in Fig. 5 can be expressed as:

$$\Delta P_{droop} = -\frac{f_{sys} - f_{nom}}{R} \quad (22)$$

Values of 3%-5% are common for $1/R$ in conventional generators [18]. Reference [19] applied droop characteristic shown in Fig. 4 on DFIG to provide a frequency regulation capability. Reference [8] adds the rate of change of frequency (ROCOF) loop, which has been shown in Fig. 5, to support primary frequency response.

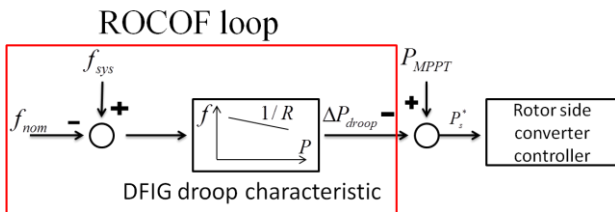


Figure 5. Droop controller.

Reference [11] describes the wind plant pitch angle control (PAC) to provide wind plant frequency regulation capability. The main idea of PAC is that the wind turbine should operate near, but not at the optimal pitch angle (de-loaded operation) so that the plant can extract more mechanical power from the wind stream as the grid frequency drops. The PAC scheme for grid frequency restoration is shown in Fig. 6.

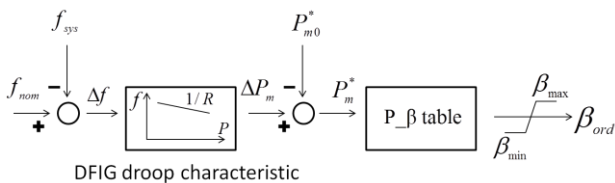


Figure 6. Pitch control.

From Fig. 6, the commanded pitch angle β_{ord} is obtained from a P_β table. The mechanical power reference P_m^* of the wind turbine is decided by the initial mechanical power of the wind turbine P_{m0}^* and the additional power ΔP_m is related to the wind plant's droop characteristic and the grid frequency change Δf . If there is a system frequency drop, the wind plant is expected to produce the additional power given by:

$$\Delta P_m = -\frac{f_{sys} - f_{nom}}{R} \quad (23)$$

Reference [20] proposes a droop assignment algorithm which is introduced in (24)-(28) for the inertial control to support the grid frequency. From (23):

$$\overline{\Delta P_{droop}} = -\frac{\overline{f_{sys}} - \overline{f_{nom}}}{R} \quad (24)$$

where the bars mean per unit quantity. Rearranging (24) gives:

$$\frac{\overline{\Delta P_{droop}}}{\overline{f_{sys}} - \overline{f_{nom}}} = -\frac{1}{R} \quad (25)$$

If the base values of the power and the frequency are multiplied to the numerator and denominator, respectively, the left hand side of (25) can be regarded as energy. The available kinetic energy can be represented by:

$$\Delta E_{k_DFIG} = \frac{\Delta P_{droop}}{f_{sys} - f_{nom}} = -\frac{1}{R} C \quad (26)$$

where C is the base values of energy. From (26), the relationship between $\Delta E_{k_DFIG,i}$ and R_i of the wind generator can be expressed by:

$$\Delta E_{k_DFIG,i} R_i = \Delta E_{max} R_0, \quad \text{for } i=1, \dots, n \quad (27)$$

where ΔE_{max} and R_0 are the maximum energy to be extracted and the pre-determined droop for R_0 , respectively. ΔE_{max} in (27) can be determined in many ways, but, in [20], it is calculated by inserting the maximum rotor speed ω_{max} . In addition, R_0 can also be determined in many ways. In [20], R_0 is determined so that wind generator with the smallest operating speed does not decrease below the minimum operating speed during the disturbance. As the result, R_i is determined by:

$$R_i = \frac{\Delta E_{max} R_0}{\Delta E_{k_DFOG,i}} \quad (28)$$

V. SUMMARY

With increasing penetration of wind energy in the grid and stand-alone system, DFIG controllers should be optimally tuned so as to optimize the performance of DFIG wind turbine system during frequency excursion. Reference [21] analyses the impacts of DFIGs and their supplementary loop on power system short-term frequency regulation. The research in the field of inertia

control for DFIG in wind energy applications has been summarized in this paper. The virtual inertia of the DFIG is defined and the virtual inertia control strategies which have been proposed in the literature are reviewed. Supplementary controllers should be well designed so that they are able to provide the functions including the inertial response, primary frequency regulation as well as wind power reserve similar to the conventional power plants.

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