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Study of multi-area frequency regulation strategy on AGC interconnected system with DFIG wind turbine

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Abstract. With wind power generation penetration increased year by year, DFIG wind turbine should actively provide inertia response and frequency response, which should be similar to the conventional generator technologies. It also should take part in area frequency regulation on AGC system. First, the frequency regulation model, multi-regional frequency regulation dynamic equivalent model and state-space equation, which are belonged to AGC system with DFIG wind turbine, are established based on the active power control of DFIG wind turbine in this paper. Then, the change of multi-regional frequency regulation on AGC system with wind turbine is analyzed. The simulation results show that if a disturbance of load occurred, multi-area frequency regulation strategy on AGC interconnected system with DFIG wind turbine could improve the performance of area frequency control when the system load occurred disturbance. It also could help area frequency return to original stable states better and faster and reduce fluctuation of system frequency.

Key words. DFIG wind turbine, active power control, AGC, the multi-area frequency regulation dynamic equivalent model, frequency regulation.

1. Introduction

The output power of wind turbine changes with wind speed and it has intermittent characteristic based on uncertainty and randomness of wind power [1]. With large scale wind power connected to the grid, the proportion of wind power in the grid is increasing. The wind power's effect on the power system becomes increasingly prominent. With wind power penetration increased, the wind turbine should have primary frequency regulation function and take part in automatic generation

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control (AGC) actively. It also should provide frequency response which should be similar to the conventional generator technologies. The researches show that DFIG wind turbine could prevent power system frequency decreased, but it only help system frequency return to constant which is near to rated frequency based on primary frequency regulation [2]. When DFIG wind turbine takes part in AGC, system frequency could return to rated value. Because wind power is on constantly changing states, complexity of AGC system with wind turbine is increased [3]. Some researchers argue that wind turbine doesn't take part in AGC because of which is controlled by wind speed and rotor control. Wind output power was equivalent to 'negative' load and wind turbine didn't take part in AGC in some literature on researching frequency regulation [4–6]. For example, in literature [7] renewable energy including wind power and solar photovoltaic were equivalent to parts of load, which didn't take part in frequency regulation. When the system load occurred disturbance, the frequency was damped only by the output power of conventional generators. This strategy neglected the frequency regulation ability of renewable energy power generation and reduced the ability of entire system which damp the frequency fluctuation. The primary frequency controlling loop of wind turbine was similar to the conventional generator in some researches on AGC system with wind turbine. This control strategy neglected special characteristic of wind turbine active power control [8].

Therefore, current researches on this technology only are considered that conventional generator(or wind turbine is equivalent to conventional generator) take part in multi-area frequency regulation. The typical AGC system model are used based on the above researches [9-11]. However, this model has not meet the demand of researching on AGC with wind turbine. So the multi-area frequency regulation equivalent model will be built in order to meet the demand of AGC system with wind turbine in this paper. The effect of improved multi-area frequency regulation strategy on AGC with wind turbine and whether the improved strategy can improve the stability of the system frequency are studied in this paper.

2. The active power control model of DFIG wind turbine

The active output power of wind turbine comes from the mechanical power extracted by turbine blades. Therefore, it is important to control active power of wind turbine through controlling the mechanical power extracted from available wind energy. According to the aerodynamic rule, the mechanical power extracted by wind turbines is computed as the formula shown in (1) [12].

$$P = \frac{1}{2} C_p(\lambda, \beta) \rho A V_W^3, \tag{1}$$

Where is P the mechanical power extracted by wind turbine, ρ is the air density, A is the swept area of blade, V_W is the wind speed. Because wind turbine can't extract all of the energy from the wind, the power coefficient $C_p(\lambda, \beta)$ is the fraction of available wind energy that wind turbine does harvest. β is the pitch angle of blade and λ is the tip speed ratio.

The tip speed ratio is computed by the following formula as the formula shown in (2):

$$\lambda=\frac{\omega_r r}{V_W}, \tag{2}$$

where ω_r is the rotor speed of blade and r is the radius of rotor. In general, the power coefficient $C_p(\lambda, \beta)$ is usually curve fitted by the manufacturers of wind turbine,

$$C_p(\lambda, \beta) = (0.44 - 0.0167\beta) \sin[\frac{\pi(\lambda - 3)}{15 - 0.3\beta}] - 0.00184(\lambda - 3)\beta, \tag{3}$$

As shown in the formula (1) and (2), the active power of wind turbine is controlled by controlling the pitch angle $\beta$and the rotor speed ω_r in general researches. The pitch angle control and rotor speed control play different roles in controlling the active power of wind turbine on different operation states [13].

Nowadays, Doubly Fed Induction Generator (DFIG) wind turbine based variable speed constant frequency becomes the mainstream wind turbine because of its favorable control performance on active and reactive power [14]. Therefore, DFIG wind turbine is taken as an example to research the influence of multi-area frequency regulation on AGC system with DFIG wind turbine in this paper.

The active power of DFIG wind turbine is controlled based on coordinated frequency control strategy about the pitch angle control and rotor control in this paper. The rotor side controller combines over speed controller, inertial controller and droop controller. Figure1 shows the active power coordinated control model of DFIG wind turbine.

Where d% is sub-optimal curve value. Without loss of generality, the value of d_0% is 10% in this paper [15]. ω_{ref} is rotor speed reference, f_{sys} is system frequency, f_{ref} is system frequency reference, P_0 is load and P_{grid} is output power.

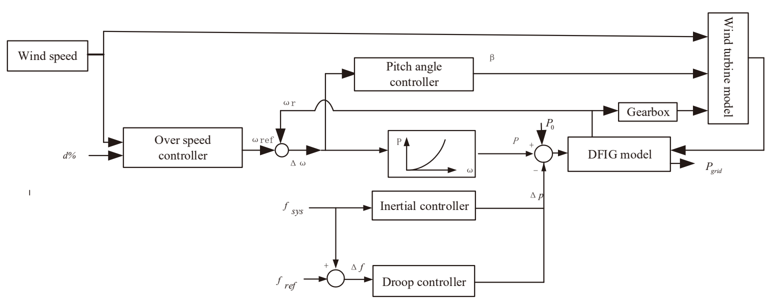

Fig. 1. The active power control model of DFIG wind turbine

3. The multi-area frequency regulation model of AGC with DFIG wind turbine

3.1. The frequency regulation transfer function of AGC with DFIG wind turbine

The output power of DFIG wind turbine varies with the wind speed, pitch angle and rotor changes, and the variation of the output power between the rated power and the zero is nonlinear. Though coordinated frequency control between the pitch angle control and rotor side control, DFIG wind turbine could obtain optimal performance under variable wind speed and grid frequency oscillation. This strategy could maximizes the stability of active output power. Therefore, when neglecting nonlinearities when research on multi-area frequency regulation on AGC system with DFIG wind turbine, the transfer function of wind turbine can be approximated by first-order lag function as the formula shown in (4).

$$G_W = \frac{\Delta P_{WG}}{\Delta P_W} = \frac{K_W}{1 + s \cdot T_W}, \tag{4}$$

Where, ΔP_{WG} is the change in DFIG wind turbine output power, ΔP_W is the change in wind power and T_W is the time constant of the wind generator. K_W is the gain constant of wind generator and it is generally valued at 1 [7].

3.2. AGC system frequency regulation model with DFIG wind turbine

In general, the increase and decrease of the load is unpredictable. It cannot realize zero error regulation a of power system frequency. The front end of active power control mode on DFIG wind turbine is added the integration adjustment of AGC frequency regulation reference to the conventional generator. It can realize automatic tracking regulation and AGC system area frequency deviation is zero. AGC system area frequency regulation model with DFIG wind turbine is shown in Figure2.

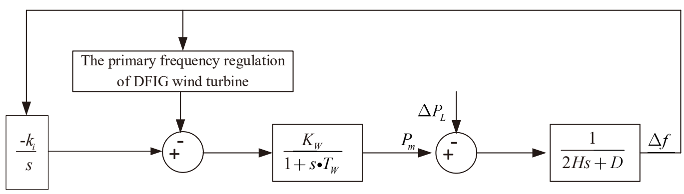

Fig. 2. AGC system frequency regulation model with DFIG wind turbine

Where, Δf is the variation of system frequency, ΔP_L is the variation of system load and $\frac{1}{2Hs+D}$ is generator-load model. In general, the value of D is 1 and the value of H is 5. $-k_i$ is integral gain coefficient of AGC regulation instruction and its value is 0.2 to 0.3s generally [8].

3.3. Interconnected power system multi-area frequency regulation dynamic model of AGC with DFIG turbine

The two areas AGC system model with DFIG turbine is built though referencing to AGC interconnected system model with conventional generator in this paper. The conventional generator is thermal power unit and DFIG wind turbine could actively take part in AGC system frequency regulation in this improved simulation mode. The two areas frequency regulation dynamic model of AGC with DFIG turbine is shown in Figure 3.

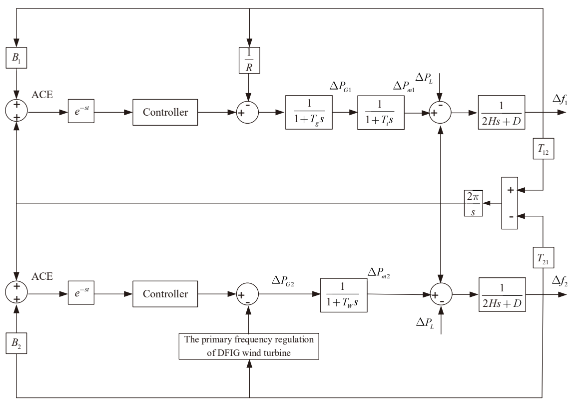

Fig. 3. The two areas frequency regulation dynamic model of AGC with DFIG turbine

The state-space equation of the equivalent model can be formulated as follows:

$$\begin{bmatrix} \Delta\dot{P}_{G1} \\ \Delta\dot{P}_{m1} \\ \Delta\dot{f}_1 \\ \Delta\dot{P}_{G2} \\ \Delta\dot{P}_{m2} \\ \Delta\dot{f}_2 \end{bmatrix} = \begin{bmatrix} -1/T_g & 0 & -1/RT_g & 0 & 0 & 0 \\ 1/T_t & -1/T_t & 0 & 0 & 0 & 0 \\ 0 & 1/2H & -D/2H & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & X \\ 0 & 0 & 0 & 1/T_w & -1/T_w & 0 \\ 0 & 0 & 0 & 0 & 1/2H & -D/2H \end{bmatrix} \begin{bmatrix} \Delta P_{G1} \\ \Delta P_{m1} \\ \Delta f_1 \\ \Delta P_{G2} \\ \Delta P_{m2} \\ \Delta f_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -1/2H \\ 0 \\ 0 \\ -1/2H \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \Delta P_{L1} \\ 0 \\ 0 \\ \Delta P_{L2} \end{bmatrix}, \tag{5}$$

Where $X = 2\pi(k_{wp} + k_{wi} + 0.1P_{MPPT}/\omega_{MPPT} - 1.2) + 1/R$. It is got by primary frequency control of DFIG wind turbine.

4. Simulations

The mean of TBC is tie-line bias frequency control model. In general TBC-TBC model is used in studying on AGC system frequency regulation with DFIG wind turbine. Area control error (ACE) of this control model is written as the formula shown in (6). where, $B_i$is the frequency deviation coefficient of the area i, Δf_i is the frequency deviation of the area i and ΔP_{tie} is the tie-line switching power deviation [3]. TBC-TBC model will be used in this paper.

$$ACE_i = B_i \Delta f_i + \Delta P_{tie}, \tag{6}$$

The interconnected power system model with DFIG wind turbine is constructed using the software Matlab/Simulink as shown in Figure4. The conventional generator is thermal power unit in this model. The interconnected power system simulation model parameters is written as shown in Table1.

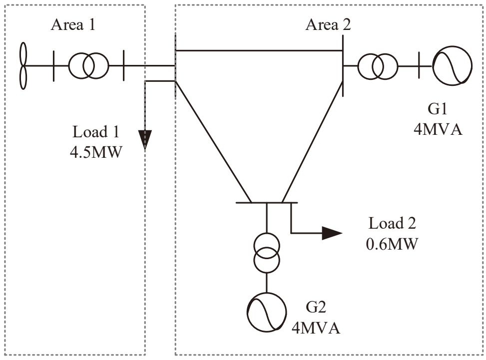

Fig. 4. Interconnected power system model

Table 1. Interconnected power system simulation model parameters

Thermal power unit	value	DFIG wind turbine	value	AGC	value
R	5%	T_W	0.2	T_{12} (T_{21})	3.42
T_g	0.1				
T_t	0.3				

The initial system is normally operating at 50Hz and load 2 is not connected. Load 2 is connected in power at $t = 2\,\mathrm{s}$. The area 2 frequency is auxiliary regulated by active power from area 1. The variables of system frequency in area1 and area2 and the tie-line switching power deviation is simulated based on different operation states of DFIG turbine as shown in Figure 5 to 6.

As conventional researches, DFIG turbine could not take part in AGC frequency regulation. Its output active power is equivalent to negative load , which is attached in interconnected power system. As red dashed line shown inFigure5, system frequency dropped when system load was occurred disturbance. The frequency fluctuation was restrained though the primary and second frequency regulation of conventional generator in interconnected power system. The frequency returned to the new steady-state value. But it didn't return to the level before occurred disturbance. The system frequency could be returned to rated value though taking long time or using other operation model (such as load shedding).

When DFIG wind turbine took part in AGC system frequency regulation, the frequencies in area 1(blue dotted line) and area 2 (green full line) all happened change because load 2 was connected in area 2 as shown inFigure5. The frequency of area 1, which combined DFIG wind turbine, drooped because load was occurred disturbance in area 2. And it could return to initial frequency state though short period time. The active power of area 2 could be got supported from area1 because DFIG wind turbine could respond the frequency change in interconnected power system as shown inFigure5 to 6. It could effectively decrease the amplitude of frequency dropped in area2 and help frequency of area 2 return to initial frequency state before disturbance.

In conclusion, if DFIG wind turbine actively took part in AGC system, it would play a more positive role on interconnected system frequency regulation than conventional researches. The time of regulation interconnected system frequency regulation would be reduced on this improved operation strategy. This improved operation strategy is also advantageous to operation of convectional generator.

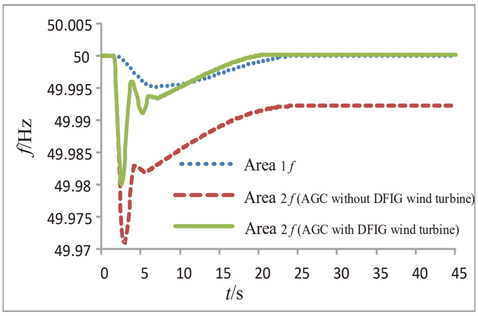

Fig. 5. Frequency variation curve of interconnected power system

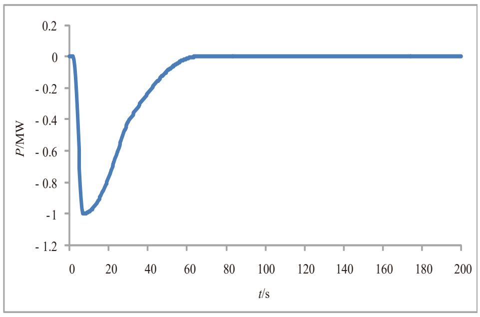

Fig. 6. Tie-line power variation curve of interconnected power system

5. Conclusion

The multi-area frequency regulation transfer function and model of AGC with DFIG wind turbine were built though adding area frequency regulation of AGC system based on controlling active power of DFIG wind turbine. The two areas frequency regulation dynamic model and state-space equation AGC with DFIG turbine were also obtained. It could provide a reasonable model of the interconnected system on researching AGC system multi-area frequency regulation with DFIG wind turbine.

The multi-area frequency regulation strategy on AGC interconnected system with DFIG wind turbine was improved based on convectional strategy. When the interconnected system load is occurred disturbance, DFIG wind turbines can actively respond to the change of interconnected system frequency. It can provide necessary active power to improve the area frequency regulation performance of interconnected system. It also can improve the dynamic process of frequency regulation and suppress the fluctuations of system frequency. It has certain superiority and rationality compared with conventional research results.

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