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Performance Investigation of Wind Turbine Induction Generators connected with a Single-Area Power System

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Abstract

Wind turbine power is a vital source of renewable energy and accounts for major plants in generating electricity in various countries. The aim of this paper is to develop the physical model of three types of wind-turbine induction generators and to investigate their impacts on the frequency in a single-area power system. The generator types are as follows: (i) squirrel cage induction generator (SCIG); (ii) doubly-fed induction generator (DFIG) and (iii) brushless doubly-fed induction generator (BDFIG). The analysis scenario is demonstrating the effect of variable wind speeds on the grid frequency under load variations. The simulation results show that BDFIG achieves better performance in comparison with DFIG and SCIG in terms of maintaining the grid frequency.

Keywords: Wind turbine power, SCIG, DFIG, Brushless DFIG, load frequency control.

1. Introduction:

The necessity for growing use of renewable energy sources has been realized as a result of daily increases in electrical energy demand, increased attention to environmental concerns, and declining fossil fuel availability. Tidal wave, solar irradiation, Wind, biomass, and fuel cells are all potential sources of such energy. Wind energy is the most common and widely used option among all of the alternatives mentioned above. Regulators and operators of power systems are concerned about the increased penetration of wind energy into present power grids because wind energy convertors traditionally do not engage in frequency control or Automatic Generation Control (AGC) systems. A high penetration of wind power into power systems can lead to a reduction of total system inertia and a high rate of system frequency deviation for any fluctuations in the load. There are various factors that affect on increasing wind power efficiencies, which are: (i) the number of blades, (ii) pitch control system, and (iii) tip-speed ratio relates with power coefficient [1]. Because of the risks of oscillating wind turbine generators when connected to the grid, knowing the characteristics of the different WTGs and studying their performance is very vital in order to identify and fix the causes of problems. A conventional type of wind power (WP) generator known as a squirrel cage induction generator is used in several existing electrical power systems (SCIG), on the other hand, is not the greatest type of WP because it has a negative impact on power system stability. DFIG is the most extensively used type in the business when compared to the others because of its ruggedness, high efficiency, and energy yield.

Another type of DFIG is brushless DFIG also known as Brushless Doubly-Fed Machine, which is considered the best alternative to conventional DFIG and more use in wind energy systems [4], and it needs less maintenance compared to conventional DFIG due to the lack of brush equipment and slip rings [5].

2. Research aims:

Firstly, Stability analysis of the dynamic model of three types of induction generators used in wind turbine systems and design control systems in order to regulate the power extracted from variable wind energy. Secondly, Investigation the effect of wind speed fluctuations on frequency and developing a virtual inertia control strategy to stabilize the grid frequency under load and wind speeds disturbances. The considered model in this paper is shown in Fig.1.

3. The proposed power system:

The system, as shown in Fig. 1, consists of wind generation system and a local generator, with the addition of the primary and secondary frequency-regulating loops. The proposed power system is modelled as follows: (i) Dynamic model of wind turbine - induction generator (WECS); (ii) Active and reactive power control system based on vector control (for a DFIG and BDFIG) and (iii) Equivalent model of thermal power plant (Conventional Generation) with primary and secondary control system for adjusting frequency variations.

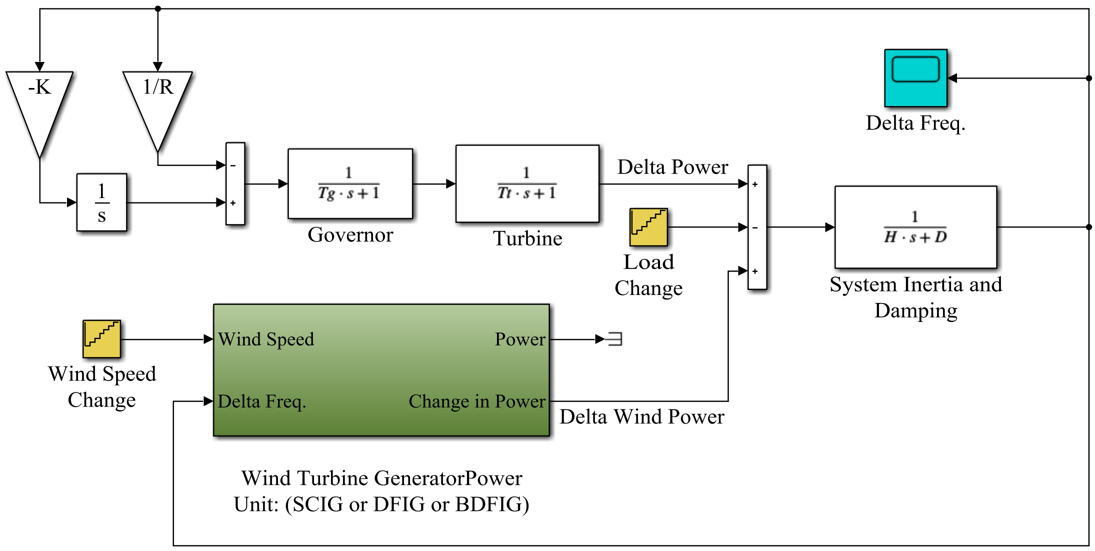


Fig.1: The structure of a wind turbine generator unit connected with a single-area power system.

The wind generation system consists of a turbine and an induction generator, where three types of generators were investigated: a squirrel-cage induction generator, a brushless DFIG, and a DFIG whose speed was controlled using PI regulators based on the vector control method.

4. Model of an Induction Generator:

The dynamic model of the induction generator in (d-q) frame which included the stator and rotor fluxes, voltages current is [2, 3]:

$$V_{sd} = R_s i_{sd} + \frac{d\Phi_{sd}}{dt} - \omega_s \Phi_{sq} \quad (1)$$

$$V_{sq} = R_s i_{sq} + \frac{d\Phi_{sq}}{dt} + \omega_s \Phi_{sd} \quad (2)$$

$$V_{rd} = R_r i_{rd} + \frac{d\Phi_{rd}}{dt} - (\omega_s - \omega)\Phi_{rq} \quad (3)$$

$$V_{rq} = R_r i_{rq} + \frac{d\Phi_{rq}}{dt} + (\omega_s - \omega)\Phi_{rd} \quad (4)$$

where: ω_s is speed of synchronously and $\omega = p\omega_m$.

The following equations link DFIG's currents and fluxes:

$$\begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix}^{-1} \begin{bmatrix} \Phi_{sd} \\ \Phi_{sq} \\ \Phi_{rd} \\ \Phi_{rq} \end{bmatrix} \quad (5)$$

The electromagnetic torque T_{em} - for DFIG - is given by:

$$T_{em} = \left(\Phi_{sd} i_{sq} - \Phi_{sq} i_{sd}\right) \quad (6)$$

The following equations link SCIG's currents and fluxes:

$$i_{ds} = \frac{\Phi_{ds} - \Phi_{md}}{L_{ls}}, i_{qs} = \frac{\Phi_{qs} - \Phi_{mq}}{L_{ls}} \quad (7)$$

$$i_{dr} = \frac{\Phi_{dr} - \Phi_{md}}{L_{lr}}, i_{qr} \frac{\Phi_{qr} - \Phi_{mq}}{L_{lr}} \quad (8)$$

Mutual fluxes are equal to:

$$\Phi_{md} = L_{ad}\left(\frac{\Phi_{ds}}{L_{ls}} + \frac{\Phi_{dr}}{L_{lr}}\right) \quad (9)$$

$$\Phi_{mq} = L_{aq}\left(\frac{\Phi_{qs}}{L_{ls}} + \frac{\Phi_{qr}}{L_{lr}}\right) \quad (10)$$

In the situation of equal winding distribution in space, the armature inductances are:

$$L_{ad} = L_{aq} = \frac{L_{lr} \cdot L_{ls} \cdot L_m}{L_{lr} \cdot L_{ls} + L_m \cdot (L_{lr} + L_{ls})} \quad (11)$$

The electromagnetic torque T_{em} for SCIG is given by:

$$T_{em} = (\Phi_{sd} i_{sq} - \Phi_{sq} i_{sd}) \quad (12)$$

The mechanical equation the induction generator is:

$$J\frac{d\omega_m}{dt} = T_{em} - T_{mech} - f\omega_m \quad (13)$$

5. Brushless DFIG:

The Brushless DFIG is a prospective substitute for the commonly used traditional DFIG, delivering higher dependability, lower capital and maintenance costs, and a considerable reduction in energy use [5,6]. It is made up of two stator coils that are electrically secluded, Power The winding is directly plugged into the power supply and Control winding feeding to Frequency converter. The majority of electrical energy passes through the power winding, which is directly linked to the power grid and hence runs at grid frequency. Only about 30% of the total power goes via the control winding, which is connected to the grid through a frequency converter. The control winding is also utilized to govern both active and reactive power. These two windings are located in the stator and are electrically isolated from each other Each of them has a different number of poles, and each coil is fed at two different frequencies. These equations are as below:

ω_p=2 πf

ω_c=ω_p-$(p_p + p_c)\omega_m$

ω_r=ω_p-$p_p\omega_m$

where: ω_p is the synchronous speed; ω_c is the control winding speed; ω_r is the rotor side speed;

$$V_{dp} = R_p i_{dp} + \frac{d\Phi_{dp}}{dt} - \omega_p \Phi_{qp} \quad (14)$$

$$V_{qp} = R_p i_{qp} + \frac{d\Phi_{qp}}{dt} + \omega_p \Phi_{dp} \quad (15)$$

$$V_{dc} = R_c i_{dc} + \frac{d\Phi_{dc}}{dt} - \omega_c \Phi_{qc} \quad (16)$$

$$V_{qc} = R_c i_{qc} + \frac{d\Phi_{qc}}{dt} + \omega_c \Phi_{dp} \quad (17)$$

$$V_{dr} = R_r i_{dr} + \frac{d\Phi_{dr}}{dt} - \omega_r \Phi_{qr} \quad (18)$$

$$V_{qr} = R_r i_{qr} + \frac{d\Phi_{qr}}{dt} + \omega_r \Phi_{dr} \quad (19)$$

The following equations link BDFIG's currents and fluxes:

$$\begin{bmatrix} i_{dp} \\ i_{qp} \\ i_{dc} \\ iq_c \\ id_r \\ iq_r \end{bmatrix} = \begin{bmatrix} L_p & 0 & 0 & 0 & L_{mp} & 0 \\ 0 & L_p & 0 & 0 & 0 & L_{mp} \\ 0 & 0 & L_C & 0 & L_{mc} & 0 \\ 0 & 0 & 0 & L_c & 0 & L_{mc} \\ L_{mp} & 0 & L_{mc} & 0 & L_r & 0 \\ 0 & L_{mp} & 0 & L_{mc} & 0 & L_r \end{bmatrix}^{-1} \begin{bmatrix} \Phi_{dp} \\ \Phi_{qp} \\ \Phi_{dc} \\ \Phi_{qc} \\ \Phi_{dr} \\ \Phi_{qr} \end{bmatrix} \quad (20)$$

BDFIG power equation (active and reactive):

$$P_P = \frac{3}{2}\left(V_{qp} i_{qp} + V_{dp} i_{dp}\right) \quad (21)$$

$$Q_P = \frac{3}{2}\left(V_{qp} i_{dp} + V_{dp} i_{qp}\right) \quad (22)$$

$$P_c = \frac{3}{2}\left(V_{qc} i_{qc} + V_{dc} i_{dc}\right) \quad (23)$$

$$Q_c = \frac{3}{2}\left(V_{qc} i_{dc} + V_{dc} i_{qc}\right) \quad (24)$$

$$P_T = P_P + P_C \quad (25)$$

$$Q_T = Q_P + Q_C \quad (26)$$

The electromagnetic torque Tem for BDFIG is calculated as follows:

$$T_{em} = \frac{3}{2}\Big(P_P\left(\Phi_{dp} i_{qp} - \Phi_{qp} i_{dp}\right) + P_C L_{mc}\left(i_{dc} i_{qr} - i_{qc} i_{dr}\right)\Big) \quad (27)$$

6. Wind turbine model:

The wind turbine converts the wind's kinetic energy Pw to mechanical energy Pm. The power coefficient of the turbine Cp represents the relationship between them. Wind power Pw is written as:

$$P_{wind} = 0.5\rho AV^3 \qquad (28)$$

The wind turbine's power output is calculated as follows:

$$P_{mech} = P_{wind} C_p(\beta, \lambda) \qquad (29)$$

where ρ, A, V, and λ are the air density (kg/m3), the area swept by the rotor blades (m[2]), the wind speed and the tip speed ratio (TSR) defined as:

$$\lambda = R_t \omega_m / V \qquad (30)$$

where R_t is radius of the turbine blade (m).

$$C_p = c_1(c_1/\lambda i - c_3\beta - c_4)e^{(-c_5/\lambda i)} + c_6\lambda i \qquad (31)$$

The physical parameters of wind Turbine C_1=0.5, C_2=116, C_3=0.4, C_4=5, C_5=21, C_6=0.0068, maximum Cp=0.5 and optimal tip speed ratio =8.

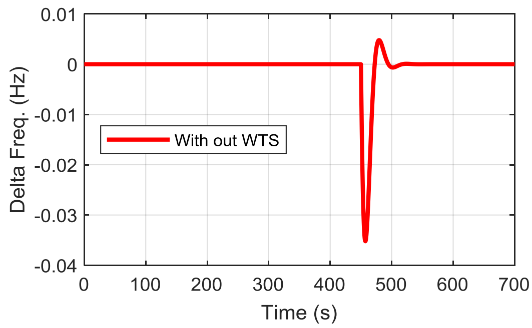
$$\frac{1}{\lambda i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{3\beta + 1} \qquad (32)$$

7. Simulation results:

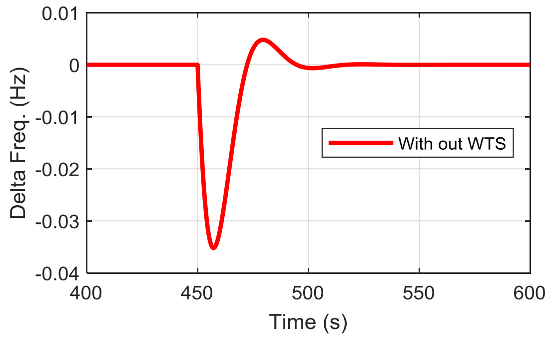
In this paper, in the beginning, a simulation is designed for three types of wind generator systems, the values of each generator are 2 MW and a test is implemented by connecting two wind generators of the same type and the contribution of wind 4MW with a conventional generator is 17 MW, which depends on changes in power generated by generators. The wind speed is varied randomly between 11 m/s to 14 m/s, and the electrical load is considered constant during 450 seconds. Suddenly the load is increased by 2%. The variation in frequency when changing wind speeds and when there is a change in load has been demonstrated for each generator type. The simulation parameters are illustrated in Appendices A, B and C. Figure 2 shows the frequency of the single-area power system with conventional synchronous generators. Figure 3 illustrates the dynamic responses when connecting SCIG or DFIG or BDFIG. It is clear that performance of the BDFIG is better compared both DFIG and SCIG, and performance of the DFIG is better compared both SCIG as the frequency vibrations are less for the presence of continuous changes in wind speeds.

Table 1. The frequency variation under disturbances.

Time (s)	Frequency Variation (mHZ)			
	Without WTS	**BDFIG**	DFIG	SCIG
0	0	**0.00**	0.00	0.000
10	0	**-21.2**	-150	-1690
20	0	**-46.0**	-229	-240
50	0	**0.90**	5.00	-33.6
101	0	**1.60**	4.40	259.3
201	0	**2.70**	4.80	29.30
301	0	**3.00**	11.5	29.50
401	0	**3.80**	12.8	28.90
450	0	**0.50**	1.20	2.400
455	-32	**-29.0**	-31.0	-0.32
501	0.6	**2.90**	11.5	26.30
601	0	**3.00**	13.3	27.80
700	0	**0.00**	0.00	0.000

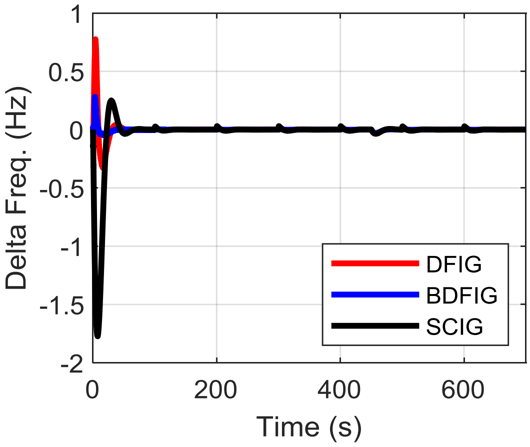


(a) Original graph.

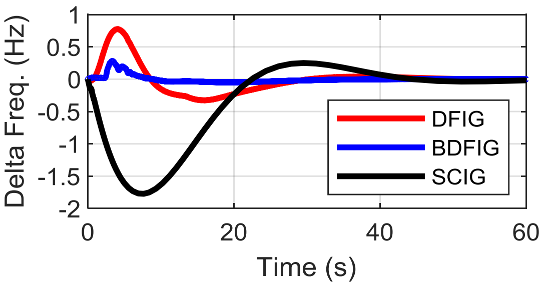


(b) Zoom range.

Fig.2: Frequency response of the single-area power system without WTS.



(a) Original graph.



(b) Zoom range.

Fig.3: Frequency response of the single-area power system connected with WTS for comparison.

7. Conclusion and future research:

This research has studied different types of generators used in wind turbines at fixed speeds SCIG and variable speeds DFIG and BDFIG with a view to increasing the penetration of wind generators to power grids. It is necessary to investigate the effect of wind speed changes on power system and determine the behavior of each of them based on the response of change of frequency. It is concluded that BDFIG is better than the other two types, either type DFIG is better than SCIG and the latter is not suitable for supporting the power system. The simulation results showed that BDFIG is suitable for wind farms because it does not contain brushes, so it does not require more maintenance compared to the conventional DFIG. The future goal of this research is to reduce frequency oscillations by designing advanced power converter based on energy storage to provide inertia to the grid under the variation of wind speeds and load.

References:

[1] Mahdi, A.J., Tang, W.H., Jiang, L., Wu, Q.H.: A Comparative Study on Variable-Speed Operations of a Wind Generation System Using Vector Control. In: International Conference on Renewable Energy (ICREPQ 2010), Granada, Spain, March 23-25 (2010).

[2] Wiam Ayrir, Ourahou Meriem, Ali Haddi, “Fuzzy logic rotor currents control of a DFIG-based wind turbine”, International Conference on Automation, Control Engineering and Computer Science (ACECS). Vol.21pp. 3-8, 2017.

[3] Ahsanullah Memon, Mohd Wazir Mustafa, Shadi Khan Baloch, Attaullah Khidrani, Touqeer Ahmed “Dynamic response enhancement of BDFIG using vector control scheme based internal model control” Indonesian Journal of Electrical Engineering and Computer Science July, 2021.

[4] R. A. McMahon, P. C. Roberts, X. Wang, and P. J. Tavner, “Performance of BDFM as generator and motor”, Electrical Power Applications, IEE Proceedings, 153(2):289-299, 2006.

[5] Tavner, P.J., Higgins, A., Arabian, H., Long, H. and Feng, Y.: ‘Using an FMEA Method to Compare Prospective Wind Turbine Design Reliabilities’, European Wind Energy Conference 2010 Technical Track, Warsaw, Poland, April 2010.

[6] A. Oraee, E. Abdi, S. Abdi, R.A. McMahon,” A Study of Converter Rating for Brushless DFIG Wind Turbines”.

[7] Ramtin Sadeghi, Seyed M. Madani, M. Ataei, R. Agha Kashkooli, Sul Ademi “Super-Twisting Sliding Mode Direct Power Control of Brushless Doubly Fed Induction Generator”, IEEE Transactions on Industrial Electronics, Nov. 2018.

[9] Thongchart Kerdphol, MasayukiWatanabe, Yasunori Mitani, Veena Phunpeng “Applying Virtual Inertia Control Topology to SMES System for Frequency Stability Improvement of Low-Inertia Microgrids Driven by High Renewables” Energies October 2019.

[10] A. Ishchenko, J.M.A. Myrzik, W.L. Kling, “Linearization of Dynamic Model of Squirrel-Cage Induction Generator Wind Turbine”, Conference: Power Engineering.Indonesian.

[11] Sheng Hu, Guorong Zhu “A Vector Control Strategy of Grid-Connected Brushless Doubly Fed Induction Generator Based on the Vector Control of Doubly Fed Induction Generator” IEEE 2016.

Appendix A. Physical parameters of BDFIG.

R_p, R_c, R_r	0.432e-3 Ω, 1.18e-3 Ω, 1.5e-3 Ω
L_p, L_c, L_r	0.7148e-3 H, 0.1217e-3 H, 0.1326e-3 H
L_{mp}, L_{mc}	0.2421e-3 H, 0.0598e-3 H
J	1200 kg.m^2
F	0.00001 kg.m^2/s
P_p, P_c	3, 2
P	2 MW
V_s	690

Appendix B. Physical parameters of DFIG.

R_r, R_s	0.0019 Ω, 0.0019 Ω
L_r, L_s	0.00556 H, 0.00398 H
L_m	0.0015 H
J	1200 kg.m^2
F	0.05 kg.m^2/s
P	2
P	2 MW
Vs	690 V

Appendix C. Physical parameters of SCIG.

R_r, R_s	1.497 e-3Ω, 1.102 e-3Ω
L_r, L_s	0.06492 e-3 H, 0.06492 e-3 H
L_m	2.1346 e-3 H
J	1200 kg.m^2
p	2
P	2 MW
V_s	690 V