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 is better performance in comparison with DFIG and SCIG in terms of maintaining the grid frequency.

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].

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.

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.

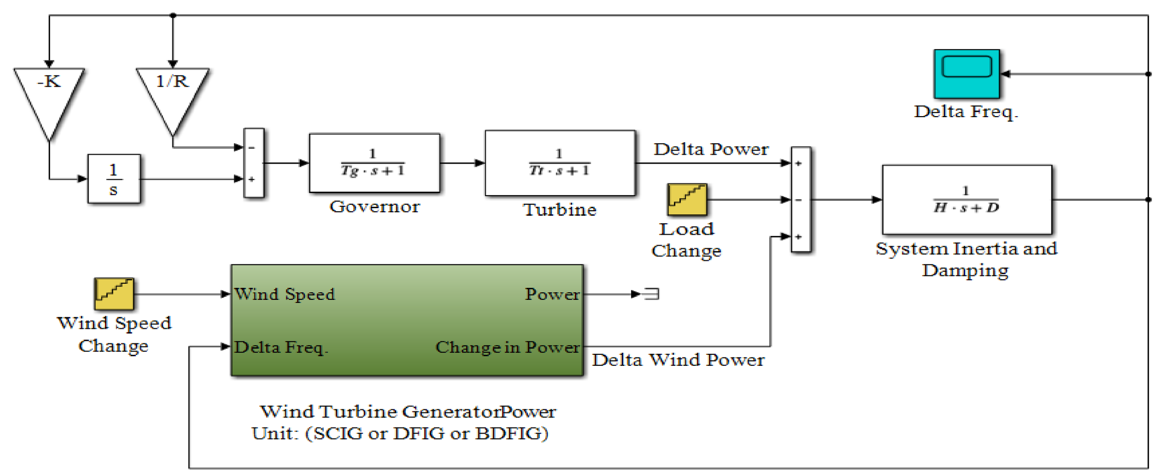


Fig.1: The structure of a wind turbine generator unit connected with a single-area power system.

objectives

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.

Mathematical Model of Induction Generator:

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

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

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

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

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:

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

The following equations link SCIG's currents and fluxes:

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

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

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:

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

Mathematical Model of Brushless DFIG

$$\omega_c = \omega_p - (p_p + p_c)\omega_m$$

$$\omega_r = \omega_p - p_p\omega_m$$

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):

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

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

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

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

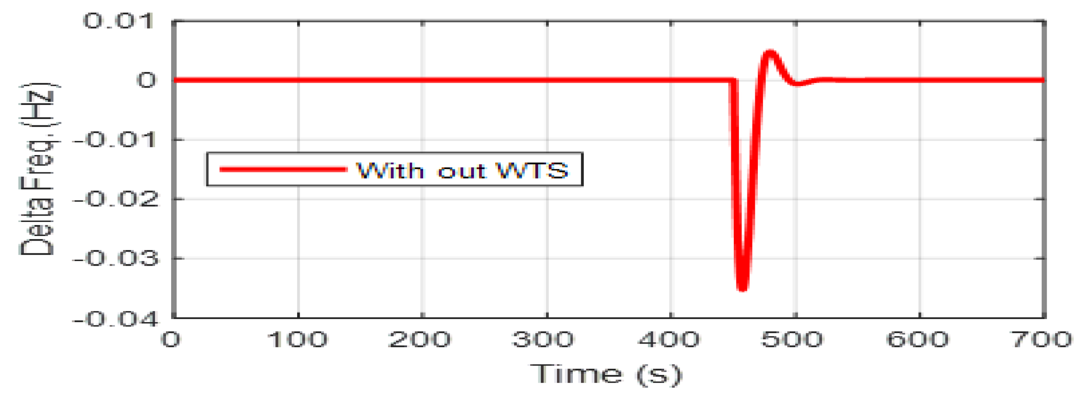
$$P_T = P_P + P_C \quad (25)$$

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

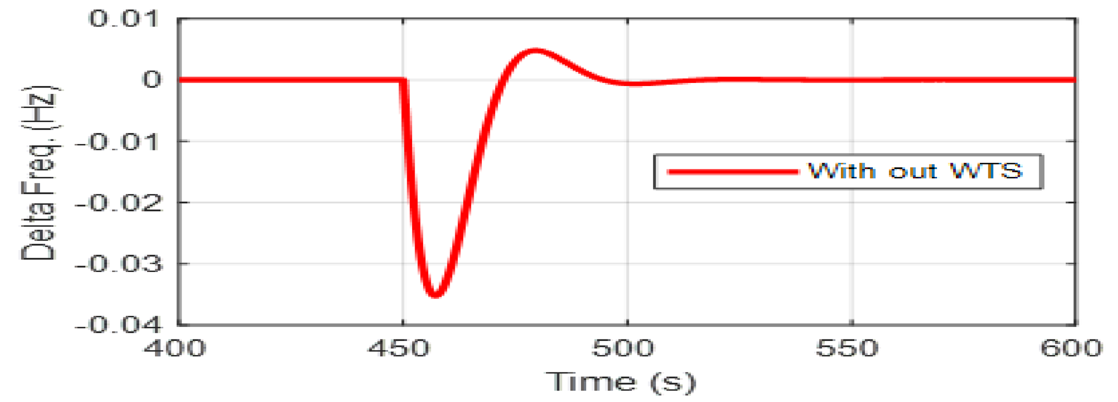
RESULTS

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. 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.

RESULTS



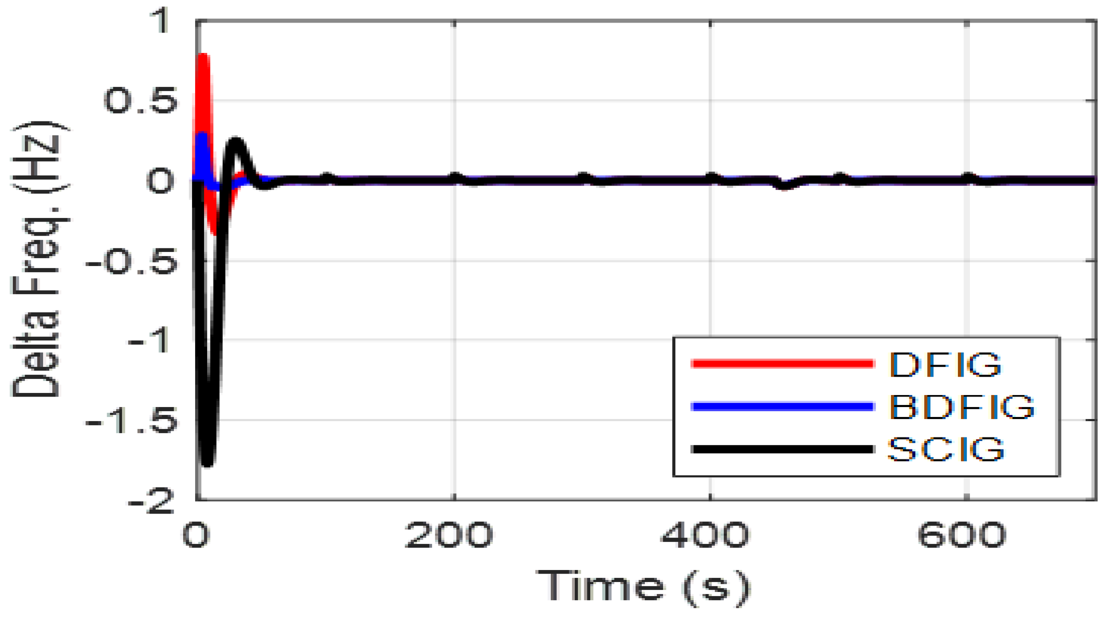
(a) Original graph.



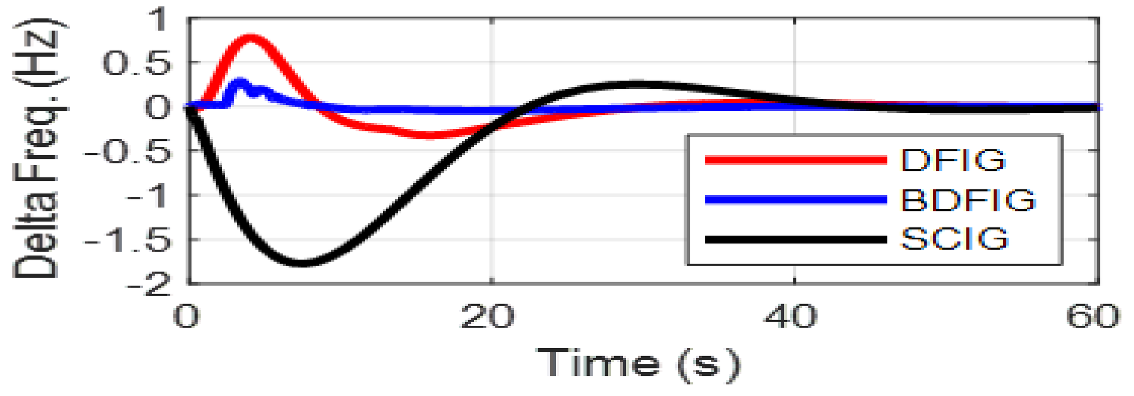
(b) Zoom range.

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

Fig.(2.b): Enlarged view for the time domain simulation in Fig.(2.a) for the period from t=400 to t=600.



(a) Original graph.



(b) Zoom range.

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

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

CONCLUTION 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

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