VOL. 11, NO. 3, FEBRUARY 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

MODELING AND SIMULATION OF A WIND TURBINE DRIVEN INDUCTION GENERATOR

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ABSTRACT

Wind Energy is one of the cheapest available renewable sources of energy. Now-a-days the demand for electricity increases drastically. A number of wind farms are already in operation and more are planned or under construction due to the increasing demand of the bulk amount of the electricity. It is must to identify the interactions between the Wind Turbines and the Power System. The objective of this paper is to design a Wind Turbine driven with Squirrel Cage Induction Generator embedded in a Power System and to predict the output of the turbine at different wind speeds. The results of the Power Coefficient, Tip Speed Ratio and Generator Speed are tabulated.

Keywords: wind turbine (WT), squirrel cage induction generator (SCIG), power coefficient (C_p), tip speed ratio (TSR).

Nomenclature

A	Area of Swept Circle by blades (m^2)
V_w	Wind Speed (m/s)
ρ	Air Density (kg/m^3)
C_p	Power Co-efficient
D	Diameter of the blade
N	Rotor Speed (rpm)
Λ	Tip-Speed ratio
ϴ	Pitch Angle (deg)
i	Current (p.u)
R	Resistance (p.u)
L	Inductance (p.u)
C	Numerical Constant
V_s,i_s	Synchronous Frame of Stator Voltage and Current vector
V_r,i_r	Synchronous Frame of Rotor Voltage and Current vector
L_m,L_σ	Mutual and Leakage Inductance
T	Torque (p.u)
S	Slip
Ψ	Flux Linkage (p.u)
ω	Rotor Speed
H_g	Inertia Constant
P	Active Power (p.u)
Q	Reactive Power (p.u)

1. INTRODUCTION

The depletion of fossil fuels from the 21st century due to its rising concerns over energy security and global warming leads to the expansion forms of interest in renewable energy. Even due to the sudden rise of oil prices from 2003, the industrial users utilising petroleum shifts their utility towards coal and natural gas. The natural gas had its own supply problems; hence wind power replaced the natural gas usages in production of electricity. The Commercial Wind Power starts fledging at a robust growth rate of about 30% every year due to its large wind resources and improved wind farm management. Wind energy is considered to be clean, sustainable and affordable energy source to improve the electricity generation. The wind energy was used by Ancient Persians to pump the water at early days. Recently, there has been a growing interest in the use of wind energy as environmental concerns are on the rise [1-2].

Innovative methods were implemented much by using improved techniques to meet the wind energy to play a major part in the future world's energy. The innovative methods reduce costs, lower the environmental impact, improve the stability, etc. While considering about the issues in the wind power, the focus on the power quality shifts to the stability problem when the wind power penetration continually increases and also due to the connections with the power system. Hence, the planning and operation of the plant becomes much important to consider the impact on the wind power when it is embedded with the power system.

To concentrate more on the problems which occurs often during operation; it is must to put much effort in modeling of the wind turbines [3]. The accuracy is a important factor while modeling these wind turbines and also simplicity is required while doing simulation in large systems. One of the major issues is the response of wind turbines (WTs) to grid disturbances, especially when the rated power of wind-turbine installations steadily increases. Therefore, it is important for utilities to be able to study the effects of various voltage sags, power quality issue and for instance, the corresponding wind turbine response [5-7].

Now-a-days many of the researchers are focusing their attention towards the response of voltage dips and short circuits in SCIG and DFIG wind farms [10]. Even then, during transient conditions, fewer measurements and simulations have been assessed for model accuracy [11-12]. These induction generators are especially used in smaller power systems which have high penetrations of the wind where the overall system inertia is reduced allowing the system less capable of dealing with changes in system generation.

The wind generating system which opts for the Squirrel Cage rotor induction generator is an attractive option because of its low cost with robust construction and also requires less maintenance when comparing with other types of generators [13]. This paper concentrates on the ability of a SCIG which is a fixed speed wind turbine dynamic model to predict the real power output changes during different wind speeds.

2. DEVELOPMENT OF WIND TURBINE MODEL

The Aerodynamics concept was first analyzed in Wind Turbine by Betz and Glauert in late 1920s and early 1930s. Wind Turbines are designed to capture the Kinetic Energy present in the wind and convert it into electrical energy. Wind Turbine power production depends on interaction between the wind turbine rotor and the wind. The mean power output is determined by the mean wind speed.

Power Output of the wind is given by;

$$P_m = \frac{1}{2}\rho A {V_w}^3 \quad (1)$$

In the above equation;
$\boldsymbol{\rho}$ = Air Density (1.225 kg/m^3);
A = Area of Swept circle by Blades (m^2);
V_w = Wind Speed.

In practice, wind turbines are limited to two or three blades due to the combination of structural and economic considerations. Hence the amount of power they can extract is closer to about 50% (0.5 times) of the available power. The ratio of the extractable power to the available power is expressed as the rotor Power Coefficient (C_p).

$$P_m = C_p \rho A {V_w}^3 \quad (2)$$

The Power Coefficient (C_p) depends mainly on the Tip Speed Ratio (λ). The TSR is the ratio of the blade tip speed to the wind speed. Hence it is given by;

$$\boldsymbol{\lambda} = \frac{\frac{N\pi D}{60}}{V_w} \quad (3)$$

where,
N is the Rotor Speed (rpm);
D is the Diameter of the Wind Turbine Blade.

While consulting with the manufacturer documentation, the power curves of the individual win turbine shows a high degree of similarity. Hence the usage of different approximations of $C_p(\lambda)$ curve is not necessary for different constant speed wind turbine in power system dynamics. In this paper, the following general approximation is used:

$$C_p(\lambda, \Theta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\Theta - C_4\Theta C_5 - C_6\right) e^{\frac{-C_7}{\lambda_i}} \quad (4)$$

where,

$$\lambda_i = \frac{1}{\frac{1}{\lambda + C_8\,\Theta} - \frac{C_9}{\Theta_3 + 1}} \quad (5)$$

Here C_1 to C_9 are constant values.

By using these equations, we can able to design the wind turbine model.

3. ASYNCHRONOUS GENERATOR

A SCIG is exclusively used in this type of modeling. The generator's rotational speed is determined by the number of poles used and also by means of frequency used in the grid. It is a well known and robust technology producing high efficiency. It is easy and relatively cheap because of mass production of the generator.
The advantages of using SCIG in WT modeling:

- There is no use of slip rings and brushes, and therefore it is almost maintenance-free.
- Mostly used generator type in Wind Turbine.
- It allows only small variations in rotor speed, the slip being -1 to -3%.
- As the speed range is small, machines using SCIG are typically called as fixed speed Wind Energy Conversion Systems.

Using the generator convention, the following VI relationships are applied in the dq reference frame:

$$V_{ds} = -R_s i_{ds} + \omega_s((L_{\sigma s} + L_m) i_{qs} + L_m i_{qr}$$
$$V_{qs} = -R_s i_{ds} + \omega_s((L_{\sigma s} + L_m) i_{ds} + L_m i_{dr}$$
$$V_{dr} = -R_r i_{dr} + s\omega_s((L_{\sigma r} + L_m) i_{qr} + L_m i_{qs} + \frac{d\psi_{dr}}{dt}$$
$$V_{qr} = -R_r i_{qr} - s\omega_s((L_{\sigma r} + L_m) i_{dr} + L_m i_{ds} + \frac{d\psi_{qr}}{dt} \quad (6)$$

where;
Indices d and q are direct and quadrature axis.
Subscript s and r are stator and rotor.
m is mutual, σ is leakage and ψ is flux linkage
The Electrical Torque is given by,

$$T_e = \psi_{qr} i_{dr} - \psi_{dr} i_{qr} \quad (7)$$

The equation of motion is given by;

$$\frac{d\omega_g}{dt} = \frac{1}{2H_g}(T_g - T_e) \quad (8)$$

The values of the various parameters depend on the generator rating.

4. WIND TURBINE EMBEDDED IN POWER SYSTEM

The block diagram of the Wind Turbine with Squirrel Cage Induction Generator embedded in a Power System is shown in the Figure-1. The generating station which generates 11kV is transmitted to the load through transmission lines when it is stepped-up and stepped-down by a transformer which forms the primary distribution.

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The distribution to the load forms the secondary distribution.

The wind turbine is modeled using the equations from 1 through 8 and a sub system is created. Then this model is coupled with SCIG. This system is embedded with the power system.

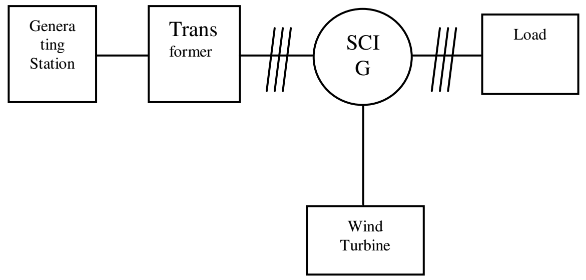

Figure-1. Wind turbine with squirrel cage induction generator.

The output of the wind turbine such as Rotor Speed, Blade Tip Speed and Power Coefficient is observed under different wind speeds which are tabulated below in Table-2. The Simulation results of rotor speed, wind speed and electromagnetic torque are also shown in figure 2-5.

Table-1. Specifications.

Wind turbine	
Diameter	28.5 m
Area of Swept Circle	638 m^2
Speed (High/Low)	39.8 rpm / 26.5 rpm
No. of Blades	3
Gear Ratio	40
Generator	
Type	Asynchronous
No. of Poles	4
Rated Output	250 KW
Main Voltage	400 v
Frequency	50
Performance data	
Rated Wind Speed	14 m/s
Cut-in Wind Speed	3.5 m/s
Cut-out Wind Speed	25 m/s
Max Power Coefficient	0.45

The specifications of the Turbine and Generator which are considered for this model are tabulated in Table-1.

The Induction generator (IG) is excited from rotor side converter. Induction generator also supplies active power to the grid through back to back converter. The grid side converter maintains zero reactive power exchange with the grid. As the rotor side converter has to handle both active and reactive power, its rating has to be high. If fixed or switching capacitors are connected to the IG terminals, the rotor side converter rating is reduced.
IG absorbs more reactive power when being in high load operation (strong winds). During low load (light wind) operation, the IG absorbs less reactive power and so the rotor side converter can be set to absorb the surplus power from the fixed capacitor preventing over excitation of IG. At the terminals of grid side converter, smoothing reactor and filters used to form a sinusoidal phase voltage and attenuate higher harmonic emission from voltage source converter switches.

5. RESULTS AND DISCUSSIONS

The results were observed by simulating at different wind speeds. The results were tabulated in table 2. From the tabulation, the maximum generator speed is obtained at 14 m/s.

The Simulation results which were obtained are shown below by using MATLAB/SIMULINK toolbox. The rotor speed, power coefficient, tip speed ratio and voltage for the different wind speeds are observed and tabulated in Table-2.

The wind speed from 10 to 24 (allowable wind speed) is considered and the output is observed through simulations. The wind speed below cut-in wind speed and the wind speed above cut-out wind speed are not considered as they may damage the blades.

The output of the wind speed is shown in Figure-2. The simulation time is 2sec.

Table-2. Values of WTG performance indices for different wind speeds.

V	Ω	Cp	λ	Vcc
10	158.1	0.4263	5.631	234.7
11	158.3	0.3903	5.127	234.5
12	158.4	0.3352	4.703	234.4
13	158.4	0.2760	4.342	234.3
14	158.5	0.2223	4.034	234.3
15	158.3	0.1764	3.759	234.3
16	158.2	0.1412	3.523	234.3
17	158.2	0.1148	3.316	234.4
18	158.3	0.0953	3.133	234.4
19	158.3	0.0809	2.968	234.4
20	158.3	0.0698	2.820	234.4
21	158.3	0.0606	2.686	234.4
22	158.2	0.05198	2.561	234.4
23	157.4	0.04224	2.437	234.2
24	156.2	0.0307	2.319	231.3

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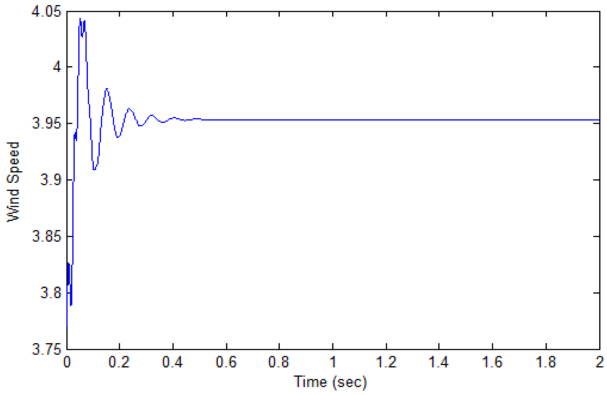

Figure-2. Output of the wind speed.

The fluctuations are shown in the Figure 2-6 and after the particular time the wind speed is maintained constant.

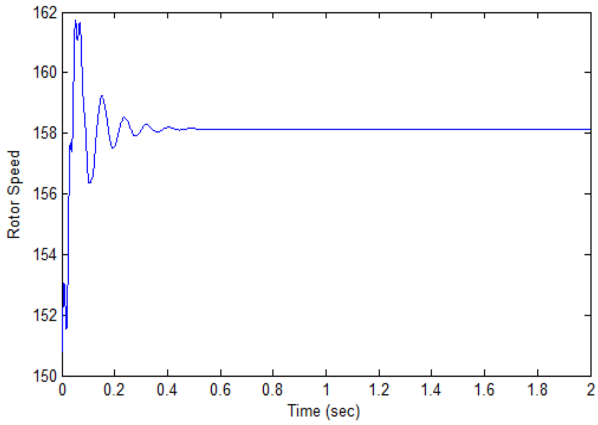

Figure-3. Output of the rotor speed.

The rotor speed output is shown in the Figure-3. When the wind fluctuates the rotor will be turned on to produce the output.

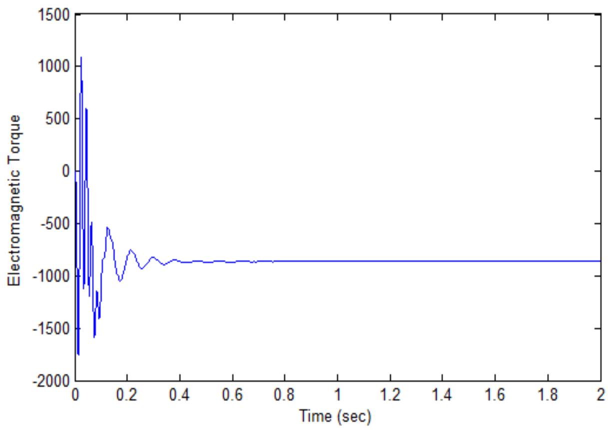

Figure-4. Output of the electro-magnetic torque.

The output of the electromagnetic torque can be determined for the wind turbine driven SCIG from the Figure-4.

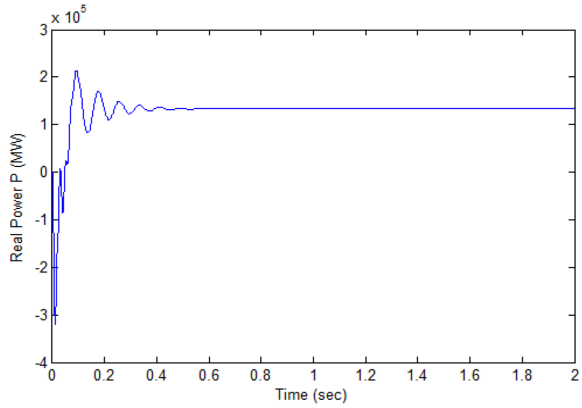

Figure-5. Output of the real power.

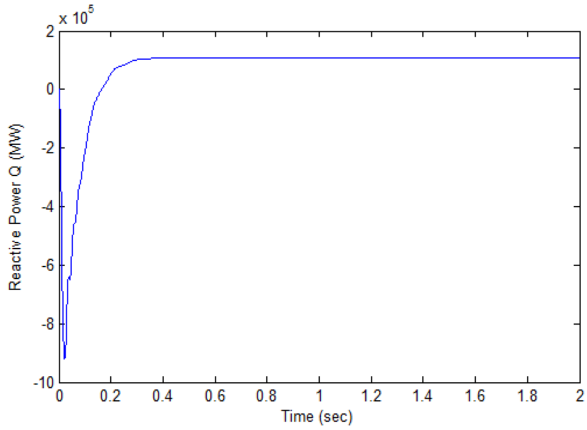

Figure-6. Output of the reactive power.

The real and reactive power of the wind turbine driven SCIG is shown in Figure 5 and 6. It never shows any fluctuation after t=1 sec.

6. CONCLUSIONS

In this paper, the behaviour of wind turbine with Squirrel Cage Induction Generator model is observed in the simulation results. The model is much suitable for investigating the impact of large-scale connection of wind power on the dynamic behavior of electrical power systems. The response from the modeled Wind Turbine such as Wind Speed, Rotor Speed, Electro-Magnetic Torque, Real and Reactive Power output exhibits a good performance.

The SCIG absorbs more reactive power when being in high load operation and during low load operation, the IG absorbs less reactive power and so the rotor side converter can be set to absorb the surplus power from the fixed capacitor preventing over excitation of IG.

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