Steady State Performance of Doubly Fed Induction Generator Used in Wind Power Generation

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Abstract: In this paper, performance of the Doubly Fed Induction Generator under steady state operating condition is presented. A mathematical model based on its equivalent circuit, output mechanical power, active and reactive power exchange between proposed system and grid has been developed. These Steady state operating parameters are obtained by solving analytical expression of mathematical model using Newton –Rapshon (NR) method with the help of MATLAB Programming. Integration of this generator with 4-Bus system has also been tested in this study under unity power factor, 0.95 leading and lagging power factors conditions. A simulation result of proposed system describes its behaviours under various operating conditions.

Keywords: Renewable Energy, Doubly fed induction generator, Wind power, Steady state analysis, Newton-Rapshon Method, Load Flow analysis.

1. INTRODUCTION

India's Renewable energy installed capacity has grown from 3.9 GW in 2002-03 to 27.54 GW in March, 2013. Wind energy has the predominated contribution in this growth. It accounts for 68% of total renewable installed capacity, followed by SHP (3.55GW), biomass (3.56GW) & solar (1.4 GW) [1]. The on-shore wind power potential is estimated to be 49,130 MW at 50 meter hub height, out of which total capacity of 18,420 MW has been installed up to Dec, 2012 in the country. India is now 5th world largest producer in the world after China, USA, Germany, and Spain [2]. Since share of wind power in the total installed power capacity is increasing worldwide, there is a strong need to develop new technology in the field such that its full potential can be harnessed. Amongst the wind generators, Doubly fed induction generators is mainly used because of their superior performance, i.e. high transfer efficiency of energy, low investment and flexible control of power and various modes of operation . It is a kind of wound rotor induction generator in which rotor winding is controlled using an AC/DC/AC IGBT-based PWM converter while stator winding of generator is connected directly to grid. Its operation based on superimposition of a variable rotor frequency of induction generator with fixed grid frequency [3]. Since steady state performance of

DFIG is influenced by increasing network complexity as well as unpredicted wind speed, it is essential to find these steady state parameters under various operating condition.

2. LITERATURE REVIEW

A literature review was conducted to analyse steady state performance of DFIG under given conditions. Alkandari et al [4] has investigated the effects of excitation voltage magnitude & its phase angle on active and reactive power under steady state condition. Meegahapola et al [5] has conducted steady-state analysis to demonstrate the loss minimization capability under various reactive power configurations. Liu and Yih Hsu [6] investigated the effect of rotor excitation voltage on steady-state stability and output power of a doubly fed induction generation. Padrón and Lorenzo [7] proposed the mathematical approach to find steady-state parameters of the DFIG.

3. STEADY STATE ANALYSIS OF DFIG

Steady state performance of DFIG is influenced by increasing network complexity as well as unpredicted wind speed, it is essential to find these steady state parameters under various operating condition. It is also for good dynamic modelling of system. These variables can be used as an initial value for dynamic model.

3.1 Mathematical Modelling

A mathematical model based on its equivalent circuit, output mechanical power, active and reactive power exchange between proposed system and grid has developed [7].

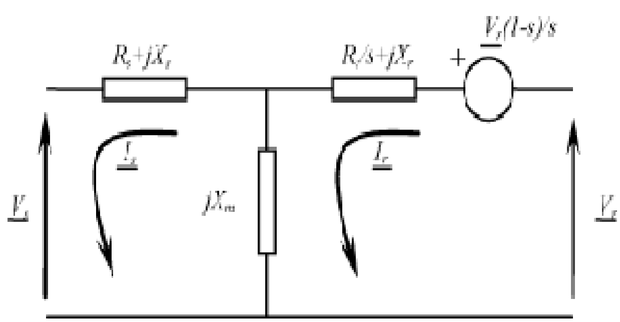

Fig.1.1: Equivalent Circuit Diagram

It is showing configured equivalent circuit diagram of doubly fed induction generator, which must satisfy the equations as:

$$V_s \angle \Phi_s = -(R_s + j(X_s + X_m))\, I_s\angle\theta_s + jX_m I_r \angle\theta_r \quad (1)$$

$V_r \angle\varphi_r = (R_r + jS(X_r + X_m))I_r\angle\theta_r - jSX_m I_s\angle\theta_s$ (2)

Non linear expressions obtained for equation 1 & 2 as given:

$f_1 = V_s cos\varphi_s + R_s I_s \cos\theta_s - (X_s + X_m) I_s \sin\theta_s + X_m I_r \sin\theta_r$ (3)

$f_2 = V_s \sin\varphi_s + R_s I_s \sin\theta_s - (X_m + X_m) I_s \cos\theta_s - X_m I_r \cos\theta_r$ (4)

$f_3 = V_r \cos\varphi_r - R_r I_r \cos\theta_r + S(X_r + X_m) I_r \sin\theta_r - SX_m I_s \sin\theta_s$ (5)

$f_4 = V_r \sin\varphi_r - R_r I_r \sin\theta_r - S(X_r + X_m) I_r \sin\theta_r + S X_m I_s \cos\theta_s$ (6)

Mechanical Power obtained from wind is transformed into electrical energy for generation, thus energy balance conditions must be fulfilled.

Mechanical power, $P_m = P_s + P_r + ({I_s}^2 R_s + {I_r}^2 R_r) = P + ({I_s}^2 R_s + {I_r}^2 R_r)$ (7)

i.e. $P_m = V_s I_s \cos(\varphi_s - \theta_s) + V_r I_r \cos(\varphi_r - \theta_r) + ({I_s}^2 R_s + {I_r}^2 R_r)$ (8)

Thus without considering losses,
$f_5 = P - V_s I_s \cos(\varphi_s - \theta_s) - V_r I_r \cos(\varphi_r - \theta_r)$ (9)

It is assumed here that all reactive power transfer will take place via stator of generator only i.e. No reactive power will transfer between grid and rotor side converter.

Reactive power Generated Q= $V_s I_s \sin(\varphi_s - \theta_s)$ (10)

$i.e\ f_6 = Q - V_s I_s \sin(\varphi_s - \theta_s)$ (11)

Mechanical power obtained from wind turbine rotor depend on power coefficient C_p, air density ρ, speed of wind U & rotor covered area A i.e.
$P_m = \frac{1}{2} * \rho * A * U^3 * C_p$ (12)

For maximum power extraction under steady condition

$P_m = \frac{1}{2} * \rho * A * U^3 * C_{p,optimum}$
$= k * U^3 = k * (\frac{V_t}{\lambda})^3== k' {w_r}^3 = k_o(1 - S)^3$ (13)

Considering of total copper losses and using equation 1.7 & 2.3, non linear equations is expressed as:

$$f_7 = P - k_o(1-S)^3 + (I_s{}^2 R_s + I_r{}^2 R_r) \quad (14)$$

Thus a set of non linear equation using 2, 3, 4, 5, 9, 11, 14 are obtained. Solutions of these equations using NR method will provide seven unknown steady state parameters for system which are rotor voltage V_r, rotor voltage angle φ_r , rotor current I_r, rotor current angle θ_r stator current I_s, stator current angle θ_s, slip S.

3.2 Methodology

Newton-Rapshon method is used to solve sets of non linear equations for to find steady state variables. Due to its low computational time and higher convergence characteristics, this method is found more efficient for large power system. In NR method, if X= X_0 is initial guesses, successive approximation to the solution are obtained using following incremented values: $X_{n+1} = X_n - J^{-1} \Delta f$

$\Delta X = X_{n+1} - X_n = - J^{-1} \Delta f$

Here, Non linear functions $\Delta f = (f_1, f_2, f_3, f_4, f_5, f_6, f_7)^T$

Unknown variables $\Delta x = (V_r\ \varphi_r\ I_r\ \theta_r\ I_s\ \theta_s\ S)^T$

Jacobian matrix, $J = \frac{\partial(f_1, f_2, f_3, f_4, f_5, f_6, f_7)}{\partial(V_r\ \varphi_r\ I_r\ \theta_r\ I_s\ \theta_s\ S)}$

3.2.1 Algorithm for proposed methodology

In the present system, it is considered that DFIG is integrated into 4-bus system which is modeled as PQ bus system. A MATLAB programming has developed to know the performance parameters of this generator which can be calculated in the following steps:

Step 1: Enter the 4-bus system line data & bus data.

Step 2: Load flow analysis is carried out using NR method to find stator voltage & its angle which is used as an input by assuming that P, Q are known.

Step 3: A set of non linear equation using 1.2, 1.3, 1.4, 1.5, 1.9, 2.1, 2.2 are solved using NR in order to find steady state parameters i.e. rotor voltage V_r, rotor voltage angle φ_r , rotor current I_r, rotor current angle θ_r stator current I_s, stator current angle θ_s, slip S . Here required initial values taken are 0.1, 0.1, 1.0, 0.1, 1.0 0.1,0 with angles in radian and others are in per unit.

Step 4: Stator Active Power Ps, Rotor Active Power Pr, Mechanical Power Pm, generated reactive power can be obtained using obtained steady state parameters.

4. RESULT AND DISCUSSION

Analysis of steady state performance of DFIG has been done for 4- bus system [11]. A load flow has been carried out by treating the bus to which DFIG is connected as PQ bus. For this the generation level of DFIG is assumed to be fixed. With the convergence of load flow, the bus voltage and bus voltage angle are calculated. In this calculation values of stator resistance Rs = 0.01 pu, stator reactance, Xs= 0.04 pu, rotor resistance Rr= 0.01 pu, rotor reactance Xr= 0.05, mutual reactance, Xm= 2.90 pu has considered [7].

Table 1.1: Bus Data for 4-Bus System

BUS	BUS TYPE	SPECIFIED VOLTAGE(pu)	GEN. (KW)	GEN. (MVAR)	LOAD (MW)	LOAD (MVAR)	Qmin	Qmax
1	Slack	1.05	0	0	0	0	0	0
2	Load	1	0	0	45	15	0	0
3	Load	1	0	0	51	25	0	0
4	Load	1	0	0	60	30	0	0

Table 1.2: 4-Bus Line Data

Starting Bus	End Bus	R (pu)	X(pu)	½ B(pu)	Tap setting
1	2	0.08	0.2	0	0
1	4	0.05	0.1	0	0
2	3	0.04	0.12	0	0
3	4	0.04	0.15	0	0

In considered system, generated power P is varying from 0.1 pu to 1.2 pu with the step of 0.1 pu as shown in Table 1.2 & Table 1.3. The performance of this generator is carried out for 0.95 leading power factor, 0.95lagging power factor and unity power factor condition. It is observed that the stator output is always positive representing the generator mode operation except at high slip operation. The rotor power nature is varying i.e. if the Pr is negative, slip is positive. The magnitude of Pr decreases continuously and slips also decreases. After attaining minimum value of Pr, for higher value of P, slip becomes negative. With increase in P, the Ps increases and so the magnitude of rotor current also increase with increase in P. The rotor voltage magnitude decreases when P increases.

Table-1.3: Steady State Parameters at Unity Power Factor

P (pu)	S(pu)	Vs(pu)	Is (pu)	Vr(pu)	Ir(pu)	Ps(pu)	Pr(pu)
0.1	0.531	0.954	-0.035	0.691	0.331	-0.033	0.186
0.2	0.411	0.959	0.037	0.601	0.333	0.035	0.114
0.3	0.326	0.963	0.121	-0.541	0.354	0.117	0.050
0.4	0.261	0.968	0.211	-0.491	0.397	0.204	-0.003
0.5	0.202	0.972	0.314	0.436	0.463	0.305	-0.054
0.6	0.156	0.977	0.426	0.375	0.541	0.416	-0.093
0.7	0.106	0.981	0.551	0.301	0.655	0.541	-0.114
0.8	0.064	0.985	0.692	0.211	0.781	0.682	-0.115
0.9	0.026	0.989	0.847	0.099	0.925	0.838	-0.067
1	-0.011	0.993	1.023	0.041	1.092	1.016	0.042
1.1	-0.041	0.997	1.211	-0.208	1.282	1.207	0.241
1.2	-0.0789	1.001	1.438	-0.411	1.499	1.439	0.568

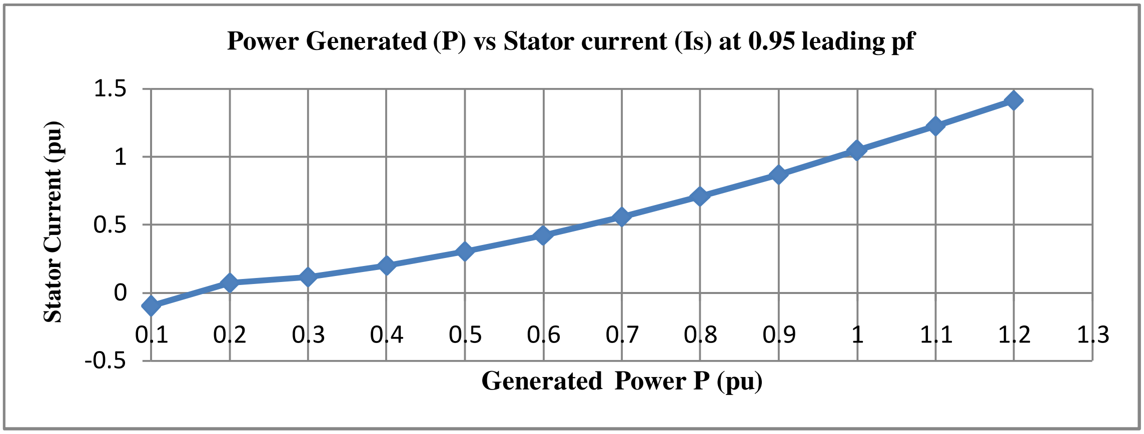

Fig 1.2: Power Generated vs. Stator Current

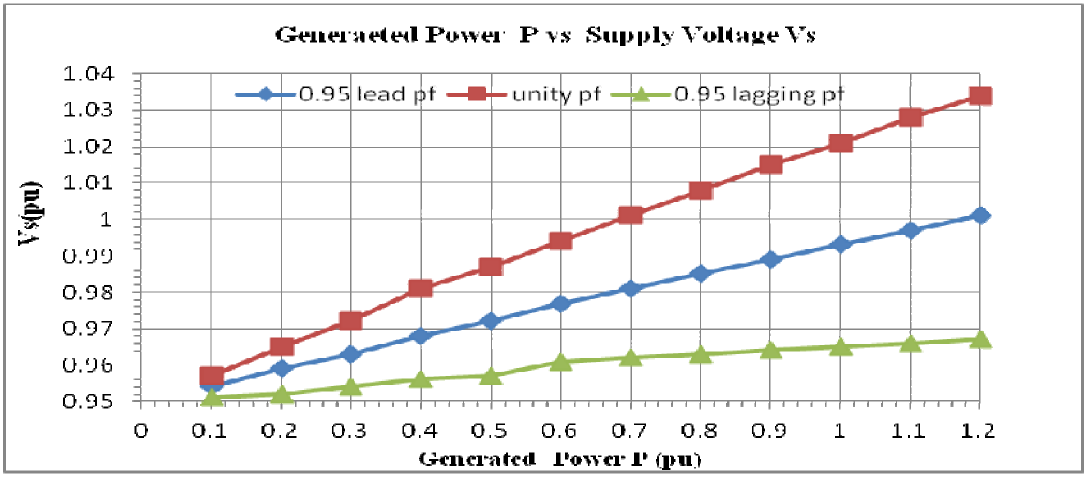

Fig 1.3: Power Generated vs. Supply Voltage

5. CONCLUSION

It has been concluded that for lower power generation slip is positive and for higher power generation slip becomes negative. The magnitude of rotor voltage is high at lower value of P which decrease with increase in P but after attaining a minimum value, it stats increasing. The stator voltage is decided by mode of operation of with system i.e. for leading power factor operation, voltage is more while for lagging power factor operation the stator voltage is less. Stator current is high for lagging power factor operation in comparison to the respective output at leading power factor. Higher stator current at lagging power factor restricts its operation for high power outputs.

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