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Modeling of Wind Generators for Load Flow Analysis

Ashima Krishna[1] and D.K. Khatod[2]

[1,2]Indian Institute of Technology, Roorkee
E-mail: [1]ashimakrishna90@gmail.com, [2]dheerajfah@iitr.ac.in

Abstract—*This paper presents power flow solution approach for a power system consisting of wind farms. The state variables associated with wind farm are combined with the nodal voltages magnitudes and angles of the transmission network in a single frame of reference for a unified iterative solution. The load flow model of a stall regulated fixed speed wind generator has been presented to understand the steady state condition of power systems with wind generators. The approach has been tested using IEEE 5 bus and 14 bus systems.*

1. INTRODUCTION

Fast consumption of fossil fuels has lead to depletion of these resources. Consequently, increasing the price of petroleum resources in the international market. There has also been a growing concern over the environmental effects of these resources. Hence, leading to research and development in the field of renewable energy as an alternative source of energy. Wind energy, is one such promising source of energy [1].

The wind turbine generator systems are employed to convert the energy possessed by blowing wind into electrical energy. They consist of a wind turbine, which has several blades, along with generator which together convert the wind energy into electrical energy. The effects of integration of these systems with the network requires special attention while planning and operating a power system [3].

Load flow analysis gives the steady state solution of a power system network. In this paper, steady state modelling of power system has been done using an iterative method for load flow, the Newton Raphson Load Flow Algorithm. Various electrical variables like voltage magnitude, phase angle and power flows have been evaluated using this method. This helped in understanding the effects of inclusion of wind farm in the system. The wind farm taken consists of Stall- Regulated Fixed Speed Wind generators. The mathematical model of wind generators is based on the steady state equivalent model of induction machine [2]-[6].

A sequential approach was used before to calculate the state variables associated with wind generators. But with this method an additional set of non linear algebraic equations had to be solved to obtain wind generator parameters. In this paper, a different approach has been used in which the state variables associated with the wind generators are combined with the state variables of the transmission network in a single frame of reference to obtain a unified iterative solution. Hence all the state variables are simultaneously adjusted during the iterative process [6].

2. WIND TURBINE GENERATOR SYSTEMS

As stated before, the wind turbine generator systems are employed to convert the energy present in the blowing wind into electrical energy. Its operation is based on the fact that wind energy is a variable source of energy which cannot be stored. A general scheme of WTGS is represented in the Fig. 1 [3]

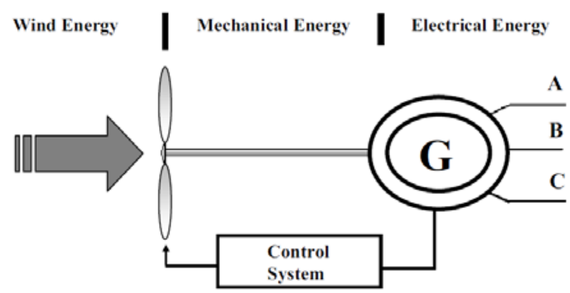

Fig. 1: General scheme of WTGS

A gearbox is commonly incorporated to match the low speed of the turbine to the high speed of generator. A Blade pitch control which is used to control the amount of power transformed, may be provided in some turbines. Commercially available wind generators installed at present are squirrel cage induction generator, doubly fed induction generator, wound field synchronous generator (WFSG), and permanent magnet synchronous generator (PMSG). The wind turbine generator systems can be classified into two types (based on rotational speed) [3]:

- Fixed speed WTGS
- Variable speed WTGS

2.1 Fixed Speed WTGS

Fixed speed WTGS are directly grid coupled conventional squirrel cage induction generator. SCIG possess superior characteristics like simpler operation, brushless and rugged construction, maintenance free and low cost. The amount of power generated of a squirrel cage induction generator varies with slip and thereby the speed of the rotor. However, the speed varies by a very small amount, approximately 1 to 2 % of the rated speed. Hence, they are commonly known as a constant or fixed speed WTGS and possess the advantage of being relatively simple. Even though their simpler design reduces their list price as compared to variable speed WTGS but their construction should be more mechanically robust as compared to latter. The variation in wind speed is directly translated into drive train torque fluctuations due to constant speed operation causing higher structural loads when compared with variable speed operation. Due to this, the decrease in cost because of less expensive generating system cancels to a certain extent [3].

The commercially used fixed speed WTGS topologies are both single and double cage squirrel cage induction generators. The big speed difference between the turbine and the squirrel cage induction generator is matched by using a gearbox. A squirrel cage induction generator consumes reactive power to establish the rotating magnetic field of the stator, which is required to be supplied from the network to its stator winding [3].

2.2 Stall Regulated Wind Turbine

The turbines can withstand strong winds (even storm) statically but not when they are spinning. Due to their design they cannot withstand extreme rotational speeds or torques. At very high values of rotational speeds or aerodynamic torques, forces present on the blades and other parts of the turbine are massive to even tear apart the turbine. Therefore their design is such that beyond a cut-out speed the brakes will slow down the turbine to rest. Even before the cut-out speed there exist a wide range of speeds for which there are control strategies (active and passive controls) to protect the turbine from the dangers that high speed winds may pose on it. The control strategies are majorly classified as [4]

(a) pitch-regulation (b) stall-regulation

In stall-regulated wind turbine the blades are designed in such a way that at high wind speeds, rotational speed or aerodynamic torque, and so the power production, goes on decreasing with increase in the wind speed above a certain value (generally not the same as the rated wind speed). The power decreases with increasing wind speeds because of the aerodynamic effects on the turbine blades (there are regions of the blade which are stalled, and hence propagates from the hub and outwards with increasing wind speeds). Blades are so designed that they perform worse (with respect to energy extraction) in high wind speeds scenario so as to protect the wind turbine so that there is no need for active controls. Stall-regulation over pitch-regulation is advantageous because of the limited capital cost of the turbine, and lower maintenance related with more moving parts. Even in stall-regulated wind turbines brakes are used to bring the turbine to a halt in extreme wind speeds [4].

The difference between pitch-regulated and stall-regulated wind turbine, is eminently noticeable during high wind speeds. Stall-regulated systems use the aerodynamic design of the blades so as to control the aerodynamic torque or the rotational speed of the turbine in the event of high wind speeds, whereas the pitch-regulated systems use active pitch control for the blades allowing it to have a constant power output above the rated wind speed. The Stall-regulated systems lack the capability of keeping a constant power output during high winds [4].

The model of wind generator used in this paper is Stall-Regulated Fixed Speed Wind Generator.

3. MATHEMATICAL MODELING

Wind generators are categorized on the basis of their operation when connected to a grid. They are modeled as induction machines. The steady state model of an induction machine has been given below in Fig. 1[6].

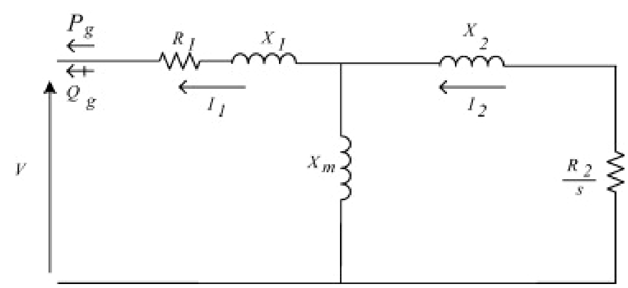

Fig. 2: Steady-state equivalent model of the induction Machine

The modelling of Stall -Regulated Fixed Speed Generator for power flow has been discussed below [6]:

3.1 Fixed-speed wind generators

These generators are directly connected to the power system network by a transformer. Their final operating point depends on the electrical frequency as well as the voltage of the node at the generator's terminals. The reactive power Q_g and active power P_g generated are determined by Equations (1) and (2), respectively, and the stator I_1 and rotor currents I_2 of the induction generator are expressed in the Equations (3)and (4) [6]:

$$Q_g(V,s) = -V^2\left\{\frac{A+Bs^2}{[C-Ds]^2+[E+Fs]^2}\right\} \quad (1)$$

$$P_g(V,s) = -V^2 \left\{\frac{K+Hs+Ls^2}{[C-Ds]^2+[E+Fs]^2}\right\} \quad (2)$$

$$I_1^2(V,s) = -V^2 \left\{\frac{[K+Hs+Ls^2]+[A+Bs^2]}{([C-Ds]^2+[E+Fs]^2)^2}\right\} \quad (3)$$

$$I_2^2(V,s) = -V^2 \left\{\frac{[Ms+Ns^2]+[Ts-Ws^2]}{([C-Ds]^2+[E+Fs]^2)^2}\right\} \quad (4)$$

Where s is the slip of the machine, V is the terminal voltage, and A to W are constants. FSWG parameters are given below [6]:

$A = R_2^2(X_1 + X_m)$,

$B = (X_2 + X_m)[X_2X_m + X_1(X_2 + X_m)]$,

$C = R_1R_2, D = X_2X_m + X_1(X_2 + X_m)$,

$E = R_2(X_1 + X_m), F = R_1(X_2 + X_m)$,

$H = R_2X_m^2, K = R_1R_2^2$,

$L = R_1(X_2 + X_m)^2$,

$M = X_mR_2(X_1 + X_m)$,

$N = X_m R_1(X_2 + X_m), T = R_1R_2X_m$,

$W = X_m[X_2X_m + X_1(X_2 + X_m)]$

Where X_m is magnetizing reactance and R_1 stator resistance.

The power converted from mechanical to electrical form (P_{conv}) is found out by using Equation (5), where $R2$ represents the rotor resistance [6]

$$P_{conv} = -I_2^2R_2\left(\frac{1-s}{s}\right) \quad (5)$$

3.2 Stall-regulated fixed-speed wind generator

The mechanical power P_m [W] extracted by this generator from wind is represented by Equation (6)

$$P_m = 0.5.\rho.c_1.\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\beta^{c_5} - c_6\right).e^{\frac{-c_7}{\lambda_i}}.A.V_w^3 \quad (6)$$

where $\lambda_i = \left[\left(\frac{1}{\lambda+c_8\beta}\right) - \left(\frac{c_9}{\beta^3+1}\right)\right]^{-1}$ and $\lambda = \frac{R.n_{gb}.\omega_s}{V_w}$

and ρ is the air density [kg/m3], A is the area swept by the blades [m2], *Vw* is the wind speed [m/s], R is the radius of the rotor [m], *n*gb is the gearbox ratio, ω_s is the angular synchronous speed [rad/s], β is the pitch angle [degrees], ω_T is the angular speed of the turbine [rad/s], and *c1* to *c9* constants which are the parameters of the wind turbine's design. Hence, assuming that the SR-FSWG is connected at node k, the power mismatches Equations are given by (7), (8) and (9), and the set of linearised equations are combined with the Jacobian matrix and the power mismatch vector corresponding to wind generator is given in Equation (10) [6]:

$$\Delta P_k = P_g(V,s) - P_{LK} - P_k^{cal} = 0 \quad (7)$$

$$\Delta Q_k = Q_g(V,s) - Q_{LK} - Q_k^{cal} = 0 \quad (8)$$

$$\Delta P_{WT1,k} = -\{P_m - P_{conv}\} = -\left\{P_m + I_2^2R_2\left(\frac{1-s}{s}\right)\right\} = 0 \quad (9)$$

$$\begin{bmatrix}\Delta P_k \\ \Delta Q_k \\ \Delta P_{WT1,k}\end{bmatrix}^j = \begin{bmatrix} \frac{\partial P_k^{cal}}{\partial \theta_k} & \left(\frac{\partial P_k^{cal}}{\partial V_k} - \frac{\partial P_g}{\partial V_k}\right)V_k & \frac{\partial P_g}{\partial s} \\ \frac{\partial Q_k^{cal}}{\partial \theta_k} & \left(\frac{\partial Q_k^{cal}}{\partial V_k} - \frac{\partial Q_g}{\partial V_k}\right)V_k & \frac{\partial Q_g}{\partial s} \\ 0 & \frac{\partial P_{WT1,k}}{\partial V_k}V_k & \frac{\partial P_{WT1,k}}{\partial s}\end{bmatrix}^j \begin{bmatrix}\Delta\theta_k \\ \frac{\Delta V_k}{V_k} \\ \Delta s\end{bmatrix}^j \quad (10)$$

where $P_g(V,s)$ and $Q_g(V,s)$ are represented by equations of FSWG, respectively, P_{LK} and Q_{LK} represent the active and reactive powers drawn by the load at bus k, respectively, and P_k^{cal} and Q_k^{cal} are active and reactive power injections given by equation (11) and (12)[6].

$$P_k^{cal} = V_k^2G_{kk} + V_k\sum_{\substack{m=1 \\ m\neq k}}^{n} V_m[G_{km}\cos(\theta_k - \theta_m) + B_{km}\sin(\theta_k - \theta_m)] \quad (11)$$

$$Q_k^{cal} = -V_k^2B_{kk} + V_k\sum_{\substack{m=1 \\ m\neq k}}^{n} V_m[G_{km}\cos(\theta_k - \theta_m) - B_{km}\sin(\theta_k - \theta_m)] \quad (12)$$

4. RESULTS AND DISCUSSIONS

The mathematical model discussed above has been implemented on two bus systems, namely IEEE 5 bus and IEEE 14 bus systems.

4.1 5-Bus Test System

A general 5-bus system is used with inclusion of wind farm comprising of forty identical SR-FSWG's operating at a wind speed of 10 m/s.

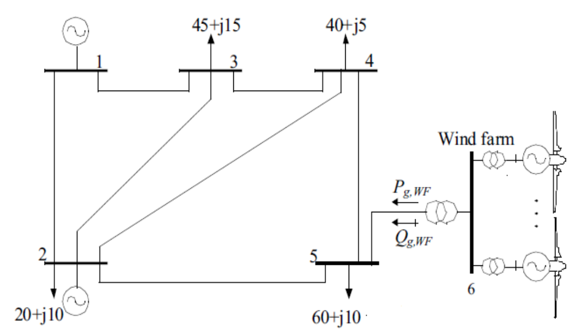

Fig. 3: Modified 5-bus system

Two cases are taken: (a) base case with no wind farm or SVC (b) case where only wind farm is there .The results have tabulated below in Table 1. The voltages are given in p.u. whereas the active power is in MW and reactive power is in MVAr. The system base is taken to be 100 MVA.

Table 1: Load flow results for 5 bus system

Results	(a)	(b)
V1	1.060	1.060
V2	1.000	1.000
V3	0.987	0.986
V4	0.984	0.983
V5	0.971	0.965
V6	-	0.933
Pg,wf	-	23.83
Qg,wf	-	-14.43

The simulated wind farm is a reactive power consumer as it does not possess the ability of reactive power control. The value of slip calculated for each generator in case (b) is -0.0033.

4.2 14 Bus Test System

Similar to the 5 bus system analysis the same 2 cases (a) and (b) have been taken here. A general 14-bus system is used with inclusion of wind farm comprising of forty identical SR-FSWG's operating at a wind speed of 10 m/s.

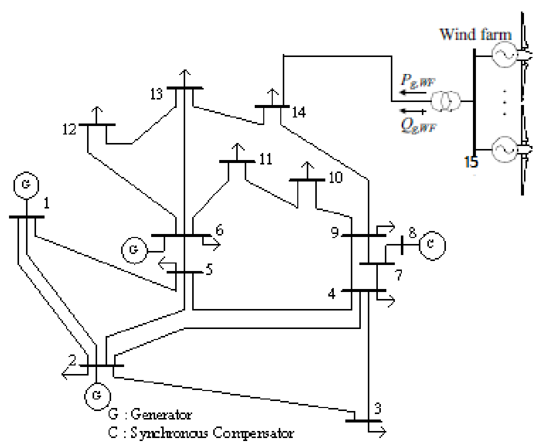

Fig. 4: Modified 14- bus system

Table 2: Load flow results for 14 bus system

Results	(a)	(b)
V1	1.060	1.060
V2	1.045	1.045
V3	1.045	1.048
V4	1.030	1.036
V5	1.038	1.043
V6	1.070	1.070
V7	1.019	1.027
V8	1.020	1.051
V9	1.018	1.025
V10	1.019	1.025
V11	1.040	1.044
V12	1.052	1.051
V13	1.045	1.044
V14	1.011	1.006
V15	-	0.974
Pg,wf	-	23.83
Qg,wf	-	-15.27

The wind farm is connected to the grid and it draws reactive power from the system. The value of slip calculated for each generator in case (b)-0.0030.

Data required for analysis has been given in Appendix-A.

5. CONCLUSION

An approach to include wind generators in the load flow analysis has been presented in this paper. A steady state mathematical model of SR-FSWG was incorporated in the Newton Raphson Load Flow Algorithm to test the approach. The approach was tested using IEEE-5 bus and 14 bus systems. It was observed that by using this approach all the state variables were obtained simultaneously and quadratic convergence was maintained.

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APPENDIX- A

-SR-FSWG Parameters

The data for wind farm is:

Wind farm transformer impedance = 0.2 pu
Stator impedance Z_1= 0.0027 + j0.025 Ω
Rotor impedance Z_2 = 0.0022 + j0.046 Ω
Magnetizing impedance Z_m = j1.38 Ω
Rated voltage V_{nom} =690 V
Rated Power P_{nom} =900 kW
Coefficients: $c1$ = 0.5; $c2$ = 116; $c3$ = 0.4; $c4$ = 0.0; $c5$ = 0; $c6$ = 5; $c7$ =21; $c8$ = 0.08; $c9$ = 0.035;β = 0