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Performance Evaluation of Fixed Speed WTGS and ATC in Power Flow Solutions

M.Vijayakumar Naik
PG Scholar,
Department of Electrical and Electronics Engineering,
Madanapalle Institute of Technology and Science,
Madanapalle, India.

Mr.B.Chandra Sekhar, M.Tech
Assistant professor,
Department of Electrical and Electronics Engineering,
Madanapalle Institute of Technology and Science,
Madanapalle, India.

ABSTRACT:

In this paper, an increased penetration of wind turbine generating systems into power grid calls for proper modeling of the systems and incorporating the model into various computational tools used in power system operation and planning studies. This project proposes a simple method of incorporating the exact equivalent circuit of a fixed speed wind generator into conventional power flow program. Available Transfer Capacity (ATC) of the power system also observed without and with fixed speed wind generator. The effectiveness of the proposed method is then evaluated on a simple system as well as on the IEEE 30- and 57-bus systems. The results of the simple system are also compared with MATLAB/SIMULINK using dynamic model of wind generating system given in Sim Power Systems blockset.

I.INTRODUCTION:

Wind is the fastest growing renewable energy technology in the world and is considered as the most cost effective way of generating electrical power from renewable sources. The principle of a wind turbine generating system (WTGS) is based on two well known processes: conversion of kinetic energy of moving air into mechanical energy, and conversion of mechanical energy into electrical energy. The integration of WTGS into power grid has increased significantly in recent years [1]. In fact, worldwide installation of wind turbines has increased from about 5 GW in 1995 to more than 275 GW in 2012 [2]. Increased penetration of wind generators into power grid calls for proper modeling of the WTGS and incorporating the model into various computational tools used for steady state and dynamic analyses of power systems.

A WTGS can be classified into fixed speed, limited variable speed and variable speed [3,4]. Most of the earlier wind farms used fixed speed stall-controlled wind turbines [5]. However, the present trend is to use variable speed WTs that employ DFIGs. In both cases, it is very important to incorporate the model of WTGS into existing computational tools used in power system studies. This paper proposes a simple method of incorporating the exact equivalent circuit of a fixed speed wind generator into a power flow program that does not require any modification to source codes of the program. The method simply augments the network by two internal buses of the generator to include all parameters of the exact equivalent circuit of the generator. The proposed method is then tested on a simple system as well as on the IEEE 30- and 57-bus systems.

II. POWER FLOW METHOD :

Power flow is one of the most important computational tools used in power system operation and planning studies. It solves the active and reactive power equations to find bus voltage magnitudes and phase angles. The injected active power (Pi) and reactive power (Qi) into bus i of an n-bus power system can be written as

$$P_i = V_i^2 G_{ii} + V_i \sum_{j=1,\neq i}^{n} V_j (B_{ij} \sin\delta_{ij} + G_{ij} \cos\delta_{ji}) \quad (1)$$

$$Q_i = -V_i^2 B_{ii} + V_i \sum_{j=1,\neq i}^{n} V_j (G_{ij} \sin\delta_{ij} - B_{ij} \cos\delta_{ji}) \quad (2)$$

Here Y = (G + jB) and dij = (di – dj). Vi and Vj are the voltage magnitude of buses i and j, respectively. di and dj are the voltage phase angle of buses i and j, respectively, and Y is the bus admittance matrix. The Newton Raphson (NR) method is commonly used to solve the above equations. The governing equation of the method can be written as

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} = [J] \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \quad (3)$$

The size of the jacobian matrix J in (3) is (nPV + 2nPQ) × (nPV + 2nPQ), where nPV is the number of P-V buses and nPQ is the number of P–Q buses in the system. The computational algorithm of the method is well described in literature [6]. For most of the well-behaved systems, the NR method usually converges in 3–6 iterations.

III. WIND POWER:

The mechanical power captured by a wind turbine (PT) can be written as

$$P_T = \frac{1}{2}\rho A V_w^3 C_p(\lambda, \beta) \quad (4)$$

Here p is the air density (kg/m3), A is the turbine blade swept area (m2), Vw is the wind speed (m/s), and Cp is performance coefficient of the turbine. Cp is a function of tip speed ratio k and blade pitch angle b, and it can be expressed as

$$C_p(\lambda, \beta) = c_1\left[\frac{c_2}{\lambda_i} - c_3\beta - c_4\beta^{c_5} - c_6\right]\exp\left(\frac{-c_7}{\lambda_i}\right) \quad (5)$$

$$\text{where } \lambda_i = \left[\frac{1}{\lambda + c_8\beta} - \frac{c_9}{\beta^3 + 1}\right]^{-1} \text{ and } \lambda = \frac{R\omega_T}{V_w} = \frac{R a_g \omega_r}{V_w}$$

Here ωr and ωt are the angular velocity (rad/s) of the turbine and the generator rotor, respectively. R is the turbine blade length (m) and ag is the gear ratio. The value of various constants (c1–c9) can be determined from manufacturer data. The above equations are very useful in designing control system of a WT to maximize its efficiency. However, the objective of this paper is to determine the power flow results of a wind integrated power system and the evaluation of control strategy of WT is beyond the scope of the paper.

A typical variation of turbine power against wind speed is shown in Fig. 1 where Vin, Vr and Vout represent the cut-in wind speed, rated wind speed and cut-out wind speed, respectively, and Pr is the rated power of the turbine. It can be noticed in Fig. 1 that the turbine power is variable only in region 2 where the wind speed varies between Vin and Vr. In other regions (1, 3 and 4) or wind speeds, the turbine power is either zero or at rated value.

Fortunately, most of the WT manufacturers provide the power curve and thus for a given wind speed, the turbine power can immediately be determined from the curve or a lookup table. In simulation Studies, it is preferable to have piece-wise mathematical expressions of the power curve estimated in region 2 (Vin 6Vw6Vr) through a quadratic function using the values of Vin, Vr and Pr. In this study, the turbine power P Tin region 2 is expressed by the following polynomial.

$$P_T = a_0 + a_1 V_w + a_2 V_w^2 + a_3 V_w^3 \quad (6)$$

The manufacturer data can be used to evaluate the coefficients using any standard curve fitting technique. Fig. 2shows a comparison of estimated power obtained with the corresponding actual values of Vestas V100-1.8 MW wind turbine supplied by the manufacturer [6]. The coefficients are obtained through 'polyfit' routine given in MATLAB using the manufacturer data extracted at discrete wind speeds (at an interval of1 m/s) from cut-in wind speed of 3 m/s to rated wind speed of 12 m/s. Thus, mathematically, the turbine power PT of Fig. 1can be expressed as

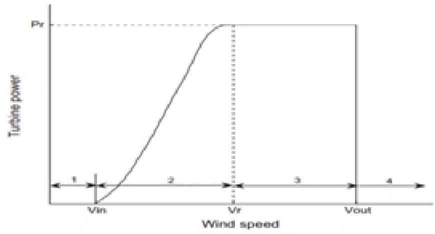

Fig. 1. Typical power curve of a wind turbine.

$$P_m = \eta_g P_T \quad (8)$$

$$P_T = \begin{cases} 0; & \text{if } V_w \leqslant V_{in} \\ (a_0 + a_1 V_w + a_2 V_w^2 + a_3 V_w^3); & \text{if } V_{in} \leqslant V_w \leqslant V_r \\ P_r; & \text{if } V_r \leqslant V_w \leqslant V_{out} \\ 0; & \text{if } V_w > V_{out} \end{cases} \quad (7)$$

A small fraction of turbine power is lost in the gearbox and the remaining power can be considered as input mechanical power pm to the generator. Thus, Here ηg is the efficiency of the gear box. The generator converts mechanical power Pm into electrical power and feeds into the grid. The objective of this study is to properly model the WTGS and incorporate the model into a conventional power flow program to evaluate the steady state results of the system.

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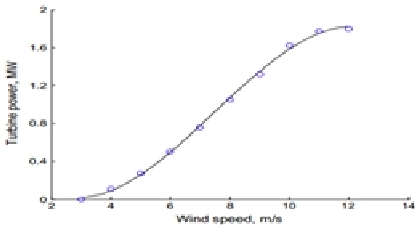

Fig.2.Comparison of estimated and actual turbine power.

IV. MODEL OF WTGS AND ITS INCORPORATION INTO POWER FLOW PROGRAM:

Consider that the SCIG of a fixed speed WTGS is connected to busk of a general power system through a step-up transformer as shown in Fig. 3. An external shunt capacitor is also connected to the generator terminal to supply reactive power. Note that a SCIG always absorbs reactive power and that can be compensated by the external shunt capacitor. The circuit of Fig. 4 is redrawn in Fig. 5 by explicitly showing two internal buses (m and r) of the generator in addition to the terminal bus t and the system bus k. Fig. 5 into input data files (bus data and line.

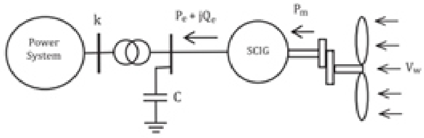

Fig. 3.Schematic diagram of a fixed speed WTGS connected to a power system through a transformer.

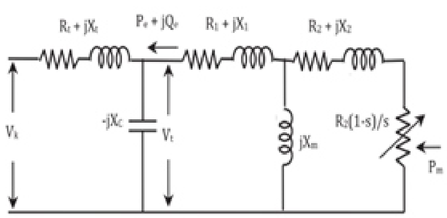

Fig. 4.Equivalent circuit of a fixed speed WTGS including the transformer and shunt capacitor.

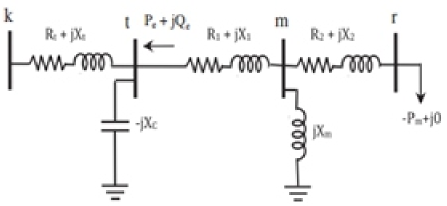

Fig. 5 Single-line representation of Fig. 4

As mentioned, a power flow program mainly determines the voltage magnitude and phase angle of all buses which are then used to compute power flow of all branches and other quantities.The complex power flow through branchR1+jX1 near bust (as shown in Fig. 5) represents the complex power (Pe+jQe) supplied by the generator at its terminal. The results associated with the internal buses (m and r) of Fig. 5 are not important and thus may be ignored or suppressed in the output of the program.

V. RESULTS AND DISCUSSIONS:

The model of a fixed speed WTGS and its incorporation into a conventional power flow program is vigorously tested on the IEEE 30-bus system. In the IEEE 30-bus system, a number of wind farms (WF) are added throughout the network. It is considered that each wind farm consists of a number of identical Vestas wind turbine (V100-1.8-MW) and SCIG (1.8-MW, 575-V, and 0.9-pf) sets. A brief description of wind farms used in this study is given in Table 1.The power curve of the WT is obtained from [7] and it has a cutin, rated and cut-out wind speed of 3, 12 and 25 m/s, respectively. Even though the curve is for a pitch-controlled variable speed turbine but the same data is used in this study because of the lack of actual data for a large size fixed speed turbine.

Table 1
Summary of various wind farms used in the IEEE 30- and 118-bus systems.

Wind farm	Number of WT and SCIG sets	Capacity in MW/MVA
A	5	9/10
B	10	18/20
C	15	27/30
D	20	36/40
E	25	45/50
F	30	54/60

The gear efficiency of the turbine is arbitrarily assumed as 95%. The parameters of the generator are considered as R1 = 0.004843 Pu, X1 = 0.1248 Pu, R2 = 0.004377 Pu, X2 = 0.1791 Pu, and Xm = 6.77 pu. The leakage reactance of the step- up transformer is assumed as 0.05 Pu. The power flow results of the above three systems are obtained by the NR method. The NR power flow program given in Power Toolbox [8] as well as developed is used for this purpose and both programs provide the same results.

(i) IEEE 30-bus system:

The single line diagram and data of the IEEE 30-bus system are given in [9]. The system is modified by adding three wind farms A, B and C (as described in Table 1) at buses 14, 26 and 30, respectively.

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The network of the system is then augmented to include the model of the wind farms. In the augmented network, the generator terminal bus (bus t in Fig. 5) of wind farms A, B and C is numbered as 31, 34 and 37, respectively. The wind speed of wind farms A, B and C is arbitrarily assumed as 12, 10 and 8 m/s, respectively. The following are the cases are studies in this paper

1.Original system (without wind farms).
2.Modified system without shunt capacitor
3.Modified system with shunt capacitor
4.Modified system at higher wind speeds without shunt capacitor
5. Modified system at higher wind speeds with shunt capacitor.

The power flow of the augmented network is then evaluated without and with shunt capacitors. The MVAr rating of shunt capacitors is considered as 25% of respective wind farm capacity in MVA. .

However, the voltage profile is improved when the shunt capacitors are added. At higher wind speeds (with shunt capacitors), the voltage profile again decreases because of drawing more reactive power.

Table 2: Comparision of voltage per unit at some buses in real power lossers (RPL) in MW of the IEEE 30 bus system.

Bus No	Case 1	Modified System with 3 Wind Farms			
		Case 2	Case 3	Case 4	Case 5
14	1.0429	1.0393	1.0484	1.0385	1.0479
26	1.0025	0.9817	1.0456	0.9726	1.0412
30	0.9953	0.9620	1.0360	0.9566	1.0330
31	-	1.0374	1.0477	1.0366	1.0472
34	-	0.9777	1.0445	0.9677	1.0395
37	-	0.9576	1.0360	0.9522	1.0330
RPL	17.528	14.421	13.487	14.660	13.550

Table 3 Comparison of the ATC in MW of the IEEE 30 bus system.

Seller/ Buyer	Case 1	Modified System with 3 Wind Farms			
		Case 2	Case 3	Case 4	Case 5
8/25	21.9	30.7	27.9	32.5	29.6
5/30	14.0	24.8	29.8	23.2	29.8
11/26	11.9	25.8	27.2	20.7	28.7
2/28	13.1	33.8	33.2	34.6	34.1

The real power system losses are also shown in in the Table 2. It has been observed that the loss reduction is higher when shunt capacitor existing. Table 3 shown the ATC values for different cases and it has observed the ATC improved in all the cases. The minimum and the maximum power for 1000 random cases are found as 8.52 MW and 41.48 MW, respectively. Note that the total capacity of 3 wind farms is 54 MW. The distribution of minimum bus voltage of the original network (buses 1–30) is shown and it indicates that the minimum voltage varies within a very narrow range (1.0045pu – 1.0053pu) possibly because of low degree of penetration of wind power (<10%). However, the minimum voltage in the augmented network including the generator terminal and internal buses has a wider range (0.9655pu – 1.0258pu). In all cases, the lowest voltage occurred at generator internal buses and which is not so important.

(ii) IEEE 57-bus system:

The single line diagram and data of the IEEE 57-bus system are given in and details are given Appendix B. The system is modified by adding three wind farms A, B, C, D, E and F (as described in Table 5.1) at buses 10, 20, 31, 39, 49 and 56, respectively.

Table 4 Comparison of voltage in per unit at some buses and real power losses (RPL) in MW of the IEEE 57-bus system.

Bus No	Case 1	Modified System with 6 Wind Farms			
		Case 2	Case 3	Case 4	Case 5
10	0.9863	1.0032	1.0197	0.9996	1.0066
20	0.9639	0.9737	1.0281	0.9443	1.0076
31	0.9372	0.9371	1.0622	0.9158	1.0490
39	0.9830	1.0084	1.0688	0.9881	1.0537
49	1.0363	1.0540	1.0893	1.0337	1.0700
56	0.9685	0.9957	1.0812	0.9775	1.0607
58	-	1.0014	1.0192	0.9977	1.0059
61	-	0.9705	1.0277	0.9389	1.0057
64	-	0.9325	1.0622	0.9108	1.049
67	-	1.0047	1.0702	0.9808	1.0527
70	-	1.0514	1.0925	1.0213	1.0666
73	-	0.9940	1.0864	0.9738	1.0723
RPL	28.574	20.814	19.308	20.790	17.059

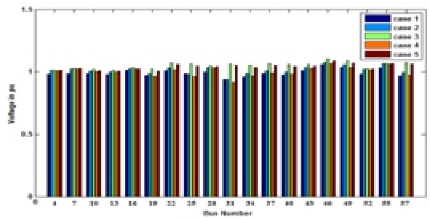

Fig. 6 Voltage profile of some buses of the IEEE 57-bus system

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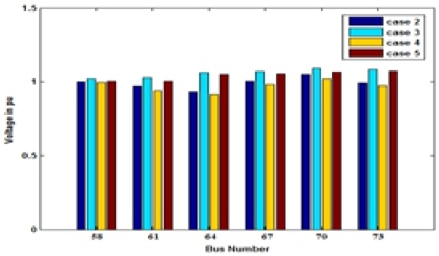

Fig. 7 Voltage profile of wind generator terminal buses of the IEEE 57-bus system.

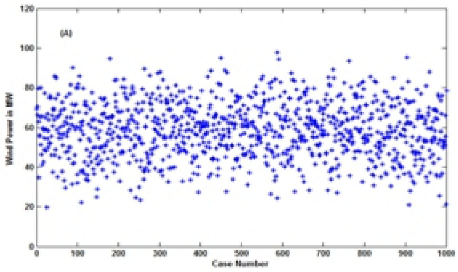

Fig. 8 (A). Distribution of results of the 57-bus system for 1000 random cases of wind speeds: wind power

Finally, the wind speed of all wind farms is randomly selected through Weibull probability density function with a shape parameter of 2 and scale parameter of 9.027 (that corresponds to an average wind speed of 8 m/s [10] using 'random' routine given in MATLAB. The power flow problem of the modified network with shunt capacitors is then repeatedly solved for 1000 random cases of wind speeds. In all cases, the NR method successfully converged within 5 iterations.

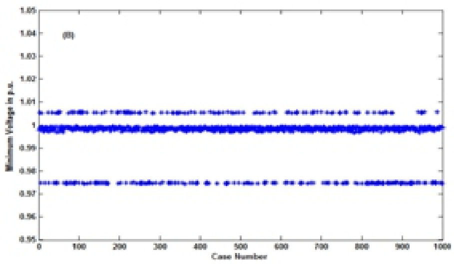

Fig. 8 (B). Distribution of results of the 57-bus system for 1000 random cases of wind speeds

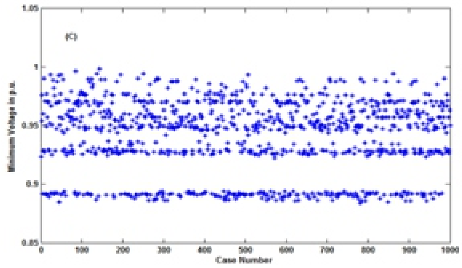

Fig. 8 (C). Distribution of results of the 57-bus system for 1000 random cases of wind speeds: minimum voltage in the augmented network.

The distribution of total injected wind power (at internal bus r) is shown in Fig. 8 (A). The minimum and the maximum power for 1000 random cases are found as 19.70 MW and 97.80 MW, respectively. The distribution of minimum bus voltage of the original network (buses 1–57) is shown in Fig. 8 (B) and it indicates that the minimum voltage varies within a very narrow range (0.9745 pu – 1.0058 pu) possibly because of low degree of penetration of wind power (<10%). However, the minimum voltage in the augmented network including the generator terminal and internal buses has a wider range (0.8840 pu – 0.9987 pu) as can be seen in Fig. 8 (C). In all cases, the lowest voltage occurred at generator internal buses and which is not so important.

VI. CONCLUSION:

A simple method of incorporating the exact equivalent circuit of a fixed speed wind generating system into a conventional power flow program has been presented in this paper. The method simply augmented the network by adding two internal buses for each generating system. The new buses have the same property as a P–Q bus and thus can easily be incorporated into any power flow program without modifying the source codes of the program. However, augmentation of input data files of the program is needed to include the model or parameters of the generating system. The effectiveness of the proposed method is vigorously tested on a simple system as well as on the modified IEEE 30- and 57-bus systems. The power flow results of the simple system were also compared with the corresponding steady state values of dynamic responses of the system and are found to be in excellent agreement. It is also found that the incorporation of wind generators does not affect the convergence pattern of the power flow program.

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