Load Flow Analysis of Distribution System Including Wind Turbine Generating System Models

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Abstract— The power world is sauntering towards eco-friendly distributed generation (DG), their integration into the distribution network postures challenges to existing load flow techniques. This paper is concerned with developing models of various types of wind turbine generating systems (WTGSs) used as distributed generation (DG) sources and demonstrating their application for steady state analysis. As wind energy is used as a DG power source, its impact on the distribution system needs to be analyzed. This requires a load flow algorithm capable of simulating both radial and weakly mesh systems along with Wind Turbine Generating Systems (WTGSs). The compensation based distribution load flow algorithm is extended including WTGS modeling in the present work. The application of the proposed models for the load flow analysis of radial systems having WTGS has been demonstrated. Based on these studies we evaluate the impact of wind based DG on the voltage profile and losses of radial distribution networks. Simulation studies have been conceded out on radial distribution systems having WTGS as DG sources to illustrate the application of the proposed models.

Keywords— Distributed Generation, Distribution load flow, Wind Turbine Generating Systems, Forward and Backward sweep, Voltage Profile, Losses.

I.INTRODUCTION

The supply of electric power to homes, offices, schools, factories, stores, and nearly every other place in the modern world is now taken for granted. Electric power has become a fundamental part of the infrastructure of contemporary society, with most of today's daily activity based on the assumption that the desired electric power is readily available. The power systems which provide this electricity are some of the largest and most complex systems in the world. They consist of three primary components: the generation system, the transmission system, and the distribution system. Each component is essential to the process of delivering power from the site where it is produced to the customer who uses it. Wind energy continues to be one of the fastest growing energy technologies and it looks set to become a major generator of electricity throughout the world.

The role of wind energy in electrical power generation is increasing day by day and new advances in power electronic Equipment's are underpinning this strategy. Wind energy is converted into mechanical power by wind turbines. This mechanical power is fed to the generator directly or through gear system. This cumulative arrangement of turbine and Generator is called a wind turbine generating unit (WTGU). A large number of wind turbine generating systems (WTGSs) are already in operation and many new systems are being planned. The integration of WTGS with the power systems is taking place at both the transmission and the distribution voltage levels. This growth in wind generation has spurred investigations, to understand the behavior of the wind turbine generating Systems (WTGSs) as well as their impact on the power grid.

As distributed generation penetrates into the distribution network its impact on the voltage profile and total power losses needs to be analyzed by appropriate load flow methods. Due to high R/X ratio of distribution lines, the performance of load flow methods used for the transmission network are inadequate for distribution systems. These methods do not make use of the structural advantage (radial / weakly mesh) of distribution system. This led to the development of separate load flow methods for distribution system. These methods are broadly classified into three categories: direct methods, backward / forward sweep methods and Newton-Raphson based methods [1]. The backward/forward sweep methods have an edge over the others as they are simple, flexible and the computational time requirement is low [1].

The basic backward/forward sweep method described in [2] is applicable for radial networks only. The practical distribution systems are weakly meshed. The compensation based distribution load flow algorithm proposed in [3] address this issue. It is improved to adapt the PV bus modeling in [4]. The method was further extended to the distribution networks containing DG's, where these are modeled as constant PQ or PV nodes [5].

Ii. Wtgs Modeling

The mechanical power converted from wind energy by a wind turbine is described as

$$P_m = \frac{1}{2}\rho A C_p(\lambda, v)V^3 \tag{1a}$$

$$\lambda = \frac{\omega \eta R}{V} \qquad (1b)$$

Where, Pm is the mechanical power developed in watts, ρ is density of air (kg/m^3), V is wind speed(m/s), C_p is power coefficient, υ is pitch angle, λ is tip speed ratio, η is gear ratio and A is the area swept by the rotor. ω is the angular velocity(rpm),R is the turbine rotor radius(m) and $c_1 - c_6$,x are constants.

The variation of power coefficient C_p with a variation of υ, λ is non linear in nature. It can be estimated by the relation.

$$C_p(\lambda, \upsilon) = c_1\left(c_2\frac{1}{\wedge} - c_3\upsilon - c_4\upsilon^x - c_5\right)e^{\left(\frac{-c_6}{\wedge}\right)} \qquad (1c)$$

Where, $$\frac{1}{\wedge} = \frac{1}{\lambda + 0.08\upsilon} - \frac{0.0035}{1+\upsilon^3} \qquad (2)$$

The induction generators are generally used in wind turbine for electricity generation and modeled with standard equivalent circuit from using the concept of a rotating transformer [6–9]. In the study of [6], Feijoo and Cidras proposed two models based on the steady- state equivalent circuit of the induction generator. In the study, wind farms with asynchronous generators are modeled as PQ or RX buses in the load flow analysis. When the WTGS node is modeled as a PQ-bus, produced active and consumed reactive power. The other model, in that study, is called RX bus model in which active and reactive powers are calculated by using equivalent circuit parameters of the induction machine. Both are solved iteratively using a Newton type algorithm. Implementation of RX model into distribution system load flow analysis is found to be problematic, therefore, excluded from this study and the PQ model is used for the analyses.

***Model-I for WTGS*:**

Let us consider an induction motor equivalent circuit referred to the stator side as given in Fig. 1. In the figure, V_s and V_r stand for the magnitude of the stator voltage and referred rotor voltage, respectively. R_{sc} and X_{sc} show short-circuit equivalent resistance and reactance, respectively. R_m resistance represents core losses and X_m shows magnetizing reactance of the motor. P_s and Q_s stand for the active and reactive power demand of the motor, respectively. From figure, recognizing the fact that $Q_r = 0$, the referred rotor voltage (V_r) can be obtained by solving well-known bi-quadratic equation given in [10] by neglecting the short-circuit losses as follows.

$$V_r = \sqrt{\frac{V_s^4 - 2P_m R_{sc} V_s^2 + P_m^2\left(R_{sc}^2 + X_{sc}^2\right)}{V_s^2}} \qquad (3)$$

From the equivalent circuit, given, in Fig.1,the reactive power balance can be written as follows

$$Q_s = X_{sc}\frac{P_m^2}{V_r^2} + \frac{V_s^2}{X_m} \qquad (4)$$

Substituting the voltage equation, Eq.(3) into Eq(4), we get

$$Q_s = \frac{V_s^2}{X_m} + \frac{X_{sc}P_m^2 V_s^2}{V_s^4 - 2P_m R_{sc}V_s^2 + P_m^2\left(R_{sc}^2 + X_{sc}^2\right)} \qquad (5)$$

Similarly, from the equivalent circuit, the active power balance can be written as

$$P_s = P_m + R_{sc}\frac{P_m^2}{V_r^2} + \frac{V_s^2}{R_m} \qquad (6)$$

And, substituting voltage equation, Eq.(3), into Eq.(6), we get the active power demand of the machine as follows

$$P_s = P_m + \frac{V_s^2}{X_m} + \frac{R_{sc}P_m^2 V_s^2}{V_s^4 - 2P_m R_{sc}V_s^2 + P_m^2\left(R_{sc}^2 + X_{sc}^2\right)} \qquad (7)$$

Equ.s (5) &(7) have a straight solution and depend on the terminal voltage magnitude, mechanical power input and the equivalent circuit [6-8].

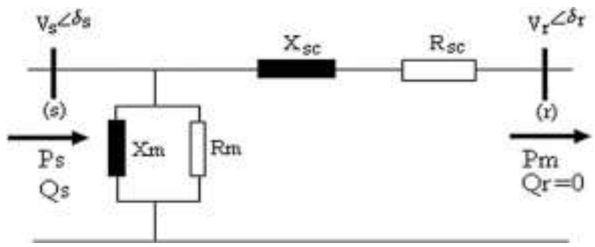

Fig.1. Induction motor equivalent circuit.

Model-II for WTGS:

Similarly, the referred rotor voltage (V_r) of the induction motor, given in Fig. 1, can also be obtained by using modified bi-quadratic equation given in [12] as follows

$$\Phi_r = \tan^{-1}\left(\frac{Q_r}{P_r}\right) \qquad (8a)$$

$$K = V_s^2 - 2P_r\left(R + X\tan\Phi_r\right) \qquad (8b)$$

$$V_r = \sqrt{\frac{K \pm \sqrt{K^2 - 4\left(R^2 + X^2\right)P_r^2\sec^2\Phi_r}}{2}} \qquad (8c)$$

From Fig.1,recognizing the fact that Q_r=0,the referred rotor voltage can be written as follows

$$\Phi_r = 0 \qquad (9a)$$

$$K = V_s^2 - 2P_r R \qquad (9b)$$

$$V_r = \sqrt{\frac{K \pm \sqrt{K^2 - 4(R^2 + X^2)P_r^2}}{2}} \qquad (9c)$$

Substituting the voltage equation, Eq.(9c) into Eq.(4), we get

$$Q_s = \frac{V_s^2}{X_m} + \frac{2X_{sc}P_m^2}{V_s^2 - 2P_m R_{sc} - \sqrt{V_s^4 - 4P_m R_{sc} V_s^2 - 4X_{sc}^2 P_m^2}}$$

(10a)

$$Q_s = \frac{V_s^2}{X_m} + \frac{2X_{sc}P_m^2}{V_s^2 - 2P_m R_{sc} + \sqrt{V_s^4 - 4P_m R_{sc} V_s^2 - 4X_{sc}^2 P_m^2}} \qquad (10b)$$

Similarly, Substituting the voltage equation, Eq.(9c) into active power balance, Eq.(6),we get

$$P_s = P_m + \frac{V_s^2}{R_m} + \frac{2R_{sc}P_m^2}{V_s^2 - 2P_m R_{sc} - \sqrt{V_s^4 - 4P_m R_{sc} V_s^2 - 4X_{sc}^2 P_m^2}}$$

(11a)

$$P_s = P_m + \frac{V_s^2}{R_m} + \frac{2R_{sc}P_m^2}{V_s^2 - 2P_m R_{sc} + \sqrt{V_s^4 - 4P_m R_{sc} V_s^2 - 4X_{sc}^2 P_m^2}}$$

(11b)

Likewise, Equations (10) and (11) have also a straightforward solution and depend on terminal voltage magnitude, mechanical power input and the equivalent circuit parameters of the induction machine except the rotor slip. It is noted that for the induction generators the mechanical power is negative due to the change on the flow of power which is transferred from ''rotor'' (bus-r) to the ''stator'' (bus-s). Hence, the mechanical power input, P_m, must be taken in negative sign for both developed models.

Since there are two solutions of real and reactive power outputs of the developed Model-II[11], the required root of the equation, given in Equations (10) and (11), must be determined. For this reason, variation of the active and reactive power output of the generator with different mechanical power input (P_m) are calculated using both expressions, for a hypothetical machine. On the other hand, the solution of Equations (10b) and (11b) remain on the feasible region. Therefore, the solution of Equations (10b) and (11b) is unique for the reactive and active power outputs of the induction generator, respectively. They can facilitate the computation of real and reactive powers of the induction generator for a specified mechanical power input and terminal voltage, in a simple way.

Presently various types of WTGU have been installed and they can be broadly classified into three categories, namely fixed, semi-variable and variable speed types[7]. The models developed here for the WTGU are intended to obtain the power output of the WTGU for a given terminal voltage and wind speed.

Pitch regulated fixed speed WTGU[7]

In this class of WTGU, the pitch angle controller regulates the wind turbine blade angle (ν) according to the wind speed variations. This designed power output Pe of the WTGU with wind speed is provided by the manufacturer in the form of a power curve. Hence, for a given wind speed Pe can be obtained from the power curve of the WTGU, but Qe needs to be computed. With the slip known, the reactive power output Qe is calculated from the induction generator equivalent circuit. Pitch regulated fixed speed WTGU power output (Pe and Qe)

$$P_e = \frac{\left[R_1\left(R_2^2 + s^2(X_m + X_{12})^2\right) + sR_2X_m^2\right]|V|^2}{\left[R_2R_1 + s\left(X_m^2 - (X_m + X_{12})(X_m + X_{11})\right)\right]^2 + [R_2(X_m + X_{11}) + sR_1(X_m + X_{12})]^2} \qquad (12)$$

$$Q_e = \frac{[X_mX_{12}s^2(X_m + X_{12}) + X_{11}s^2(X_m + X_{12})^2 + R_2^2(X_m + X_{11})]|V|^2}{\left[R_2R_1 + s\left(X_m^2 - (X_m + X_{12})(X_m + X_{11})\right)\right]^2 + [R_2(X_m + X_{11}) + sR_1(X_m + X_{12})]^2}$$

(13)

Semi Variable Speed WTGU [7]

This class of WTGU consists of a pitch controlled wind turbine and a wound rotor induction generator. The rotor circuit of the generator is connected to an external variable resistance. There are two controllers, a pitch controller and rotor resistance controller. These two controllers are designed to operate in a coordinated manner. This design guarantees that the active power output is equal to the maximum power at wind speeds below nominal and equal to rated power above nominal wind speeds. For this class of WTGU also, the manufacturer provides the designed real power out-put versus wind speed characteristics [7]. We note that the expression for Pe and Qe can be recast as a quadratic function of a new variableR2/s. Hence, even when R2 and s are unknown the quantityR2 /s (say Req) can be computed by solving the quadratic equation in Req involving Pe. To compute Qe, this value of Req is used in the modified expression for Qe. The quadratic equation for Req is as follows:

$$aR_{eq}^2 + bR_{eq} + c = 0$$

(14)

Where

$$a = P_e(R_1^2 + (X_{11} + X_m)^2 - |V|^2R_1^2) \qquad (15)$$

$$b = 2R_1P_eX_m^2 - X_m^2|V|^2$$

(16)

$$c = P_e\left(R_1^2 + (X_{11} + X_m)^2 + P_e\left(X_m^2 - (X_m + X_{12})(X_m + X_{11})\right)^2 - R_1(X_m + X_{12})^2|V|^2\right) \qquad (17)$$

Given wind speed u_w and the terminal voltage V

1. For the given u_w obtain Pe from the power curve of the WTGU (provided by the manufacturer).

2. Compute $R_{eq} = \min \left| \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \right|$ (18)

3. Knowing Req , compute Reactive power Qe as

$$Q_e = \frac{\left[R_{eq}^2 (X_m + X_{l1}) - (X_m + X_{l2}) * \left(X_m^2 - (X_m + X_{l2})(X_m + X_{l1})\right)\right] |V|^2}{\left[R_{eq} R_1 + \left(X_m^2 - (X_m + X_{l2})(X_m + X_{l1})\right)\right]^2 + \left[R_{eq}(X_m + X_{l1}) + R_1 (X_m + X_{l2})\right]^2} \quad (19)$$

The Pitch regulated fixed speed WTGS model and Semi variable speed WTGS model considered here are the Vestas unit of 1MW rating .The Induction generator circuit parameters are given in Table I.

TABLE I

Induction generator circuit parameters

Type of WTGS Model	Pitch Regulated Fixed Speed	Semi Variable Speed
R_1(pu)	0.005986	0.005671
X_{l1}(pu)	0.08212	0.15250
R_2(pu)	0.01690	0.00462
X_{l2}(pu)	0.107225	0.096618
X_m (pu)	2.5561	2.8985
X_c (pu)	2.5561	2.8985

TABLE II

Induction generator circuit parameters (Model I & II)

1.	Generator short circuit resistance(ohm)	7.81
2.	Short circuit reactance(ohm)	18.76
3.	Open circuit resistance (ohm)	1230
4.	Open circuit reactance(ohm)	500.6
5.	System rms base voltage(kV)	12.66

III. LOAD FLOW ANALYSIS USING Wtgss

As the wind generator is of induction type the bus connected to wind generator can be modeled as PQ bus in load flow algorithm. The load flow algorithm including wind generator is explained through flow chart.

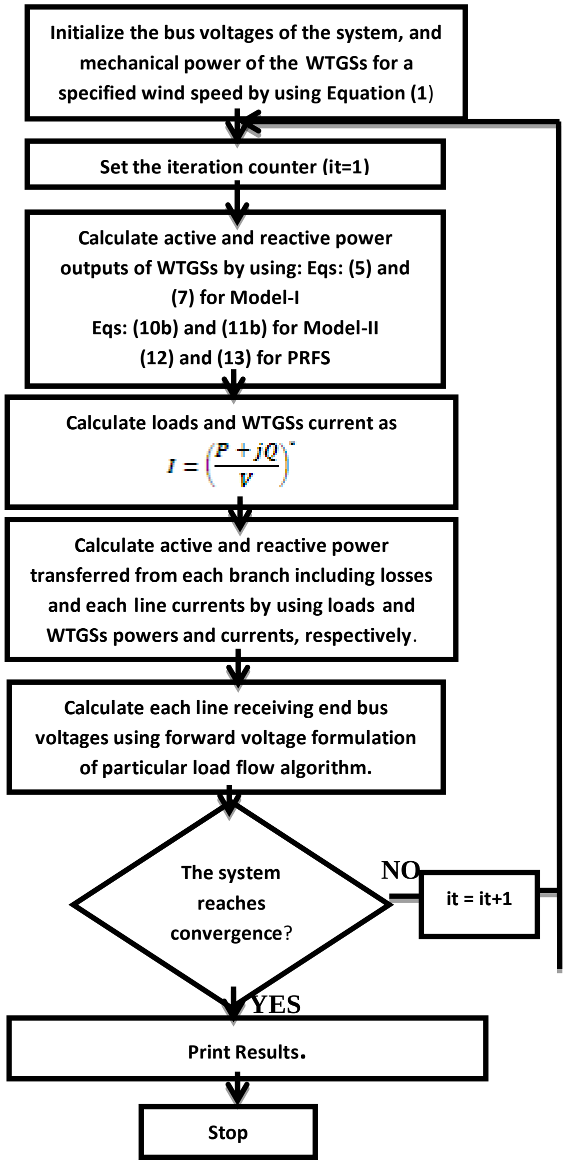

Fig. 2. Flow chart for distribution load flow with WTGS models

IV. Results And Discussion

A 33-bus distribution system is used to evaluate the effect of WTGS on the power losses, voltage profile of radial distribution system, and on the performance of load flow algorithms. Sweep-based algorithms are used and they all have been coded in

Matlab. Transformer parameters are taken from [7]. Tables III & IV represents the load flow results of the systems with and without WTGS modeled by using both developed models, pitch regulated and semi variable speed WTGS models are also depicted. Similarly, in load flow analyses, initial voltage magnitude at all buses is considered to be the same as the source bus (1.0 pu) for test system and a tolerance of 10^{-4} on convergence criteria is used. Mechanical power input is selected as P_m =1.0 MW. From the tables, it is clearly seen that the inclusion of a WTGS significantly, alters the power intake from the main substation, and total power losses of the test systems are also decreased. Moreover, the voltage magnitude of the bus at which the WTGS is connected is increased due to injected active power. The Induction machine circuit parameters and the data is taken from [11] for Model I & Model II, whereas for the remaining models i.e., Pitch regulated fixed speed and Semi variable speed is taken from [7].It is clearly observed that from the Tables III & IV developed models are more advantageous than the Pitch regulated fixed speed WTGS and Semi variable speed WTGS models.

$|V|_{pu}$ is the WTGS bus voltage.

P_m is the mechanical power input(1MW).

$P_s(MW)$ is the WTGS active power generation.

$Q_s(MVAr)$ is the WTGS reactive power demand.

$P_l(MW)$ is the active power loss.

$Q_l(MVAr)$ is the reactive power loss.

Semi Variable Speed(SVS) WTGS.

Pitch Regulated Fixed Speed(PRFS) WTGS.

ABLE III

Load flow result of the 33-bus system for Pitch Regulated and Semi Variable Speed WTGS models

Bus No.	WTGS Model	P_s (MW)	Q_s (MVAr)	P_l (MW)	Q_l (MVAr)	$\|V\|_{pu}$
6	–	–	–	0.369	0.247	0.9331
18	–	–	–			0.8959
25	–	–	–			0.9648
32	–	–	–			0.8788
6	SVS	1	0.624	0.316	0.219	0.9614
18	SVS	1	0.640			0.9243
25	SVS	1	0.616			0.9737
32	SVS	1	0.650			0.9246
6	PRFS	1	0.5665	0.285	0.197	0.9593
18	PRFS	1	0.5640			0.9218
25	PRFS	1	0.572			0.9731
32	PRFS	1	0.564			0.9202

TABLE IV

Load flow result of the 33-bus system with and without WTGS models.(Model I & Model II)

Bus No.	WTGS Model	P_s (MW)	Q_s (MVAr)	P_l (MW)	Q_l (MVAr)	$\|V\|_{pu}$
6	–	–	–	0.369	0.247	0.9331
18	–	–	–			0.8959
25	–	–	–			0.9648
32	–	–	–			0.8788
6	II	0.919	0.923	0.181	0.129	0.9680
18	II	0.919	0.923			0.9295
25	I	0.992	0.017			0.9750
32	I	0.992	0.017			0.9449

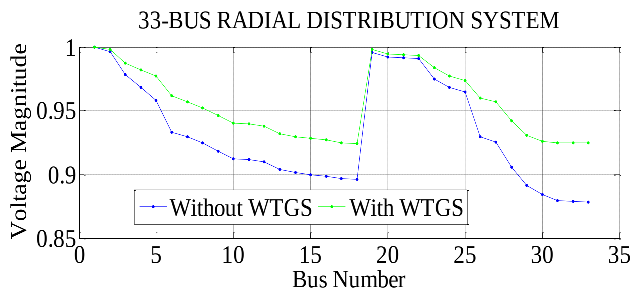

Fig. 3 Voltage profile variation of the 33-bus system for PRFS WTGS model

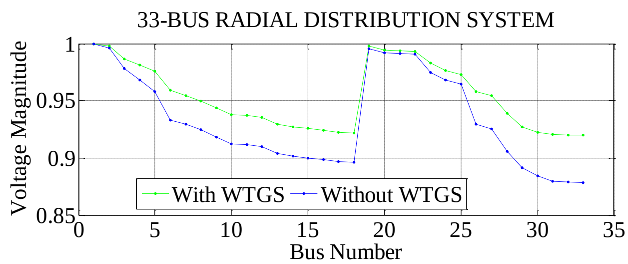

Fig. 4 Voltage profile variation of the 33-bus system for SVS WTGS model

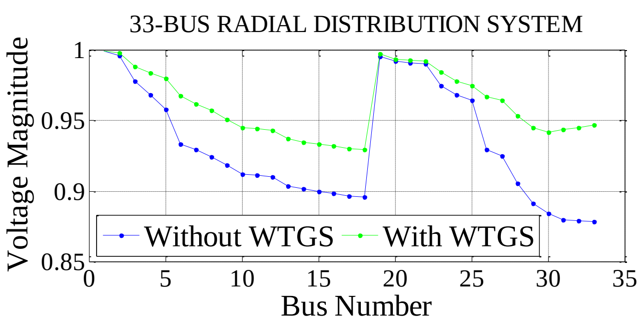

Fig. 5 Voltage profile variation of the 33-bus system (with and without WTGS models)

V. CONCLUSION

In this paper, two new models[11] for wind turbine generating systems are provided. The main advantage of the developed analytical models for WTGS is that they facilitate the computation of real and reactive power outputs for a specified mechanical power input and terminal voltages, in a simple way such that it does not require computation of any system parameters (i.e., rotor slip).Whereas the other proposed models in [7] rotor slip and power curves plays a crucial role.

These developed models [11] can overcome the computational complexity and the computational time problem. The WTGS impact on the system losses and the voltage profile is analyzed. The effectiveness of linking two buses can be studied in terms of decrement in losses and improvement in voltage profile. And the same load flow analysis can be done for other models i.e., Variable speed WTGS and Stall regulated fixed speed WTGS are also useful for the future planning of the system.

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