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Models for wind turbine generating systems and their application in load flow studies

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Abstract

This paper is concerned with developing models of various types of wind turbine generating units (WTGU) used as distributed generation (DG) sources and demonstrating their application for steady state analysis. The model for each class of WTGU developed here facilitates the computation of real and reactive power outputs for a specified wind speed and terminal voltage. The proposed models have been used to study the impact of wind speed and terminal voltage variation on the behavior of each type of WTGU. The application of the proposed models for the load flow analysis of radial systems having WTGU has been demonstrated. Based on these studies we assess the impact of wind based DG on the voltage profile and losses of radial distribution networks. Simulation studies have been carried out on a 33 bus radial distribution system having WTGU as DG sources to illustrate the application of the proposed models.

Keywords: Modelling of wind turbine generating units; Grid connected wind generators; Wind energy; Distributed generation; Load flow analysis

1. Introduction

The use of wind energy for electricity generation has been gaining popularity. A large number of wind turbine generating systems (WTGS) 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 [1–26], to understand the behavior of the wind turbine generating units (WTGU) as well as their impact on the power grid.

Results in refs. [1–13] are representative of one class of investigations, where the interest is in transient/dynamic behavior. The studies in refs. [1–6] are concerned with transient behavior of grid connected fixed speed type of WTGU. In ref. [1], a WTGU model has been developed to study the transients in its power output due to transient voltages at its terminals. In addition, ref. [1] has a brief qualitative discussion of the steady state behavior of the system with WTGU. In refs. [2–6] actual measurements of grid power fluctuations seen during starting/braking/operation of the WTGU are provided. A method of reducing these transients during starting of the WTGU has been suggested in ref. [7]. In ref. [8] models for various type of WTGU compatible with the commercially available power system dynamic simulation tools have been proposed. In ref. [9] a model for the variable speed type of WTGU has been developed and the response obtained from this model to wind variations has been qualitatively compared with the actual measured response. The studies carried out in refs. [10–13] address the transient stability issues of the power grid having WTGU. In ref. [10] the impact of connecting two different types of WTGU on the transient stability of a Spanish system has been studied. For such transient studies, detailed models for the WTGU have been proposed in refs. [11–13]. In ref. [11] the emphasis is on developing models for the DFIG and its associated controls, while refs. [12,13] deal with developing models for the wind turbine. In ref. [12] the mechanical and aerodynamic behavior of a wind turbine has been studied using a finite element analysis and this has been used to develop reduced order dynamic model for the wind turbine. The impact of various shaft models (soft shaft model, lumped model, etc.) on the estimation of critical clearing time (for faults) has been studied in ref. [13].

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The other class of investigations [14–22] attempts to address the grid-WTGU interaction in the steady state context. In refs. [14–16] the equivalent circuit model of the induction generator has been used to represent the WTGU, assuming the generator mechanical input to be known. The studies carried out in refs. [17,18] attempt to model a wind farm consisting of only the fixed speed type of wind turbine. In ref. [17] the fixed speed type of WTGU is represented using the equivalent circuit model of the induction generator as in refs. [14,15] while in ref. [18] an approximate turbine characteristic has been used in addition. Further, in both the investigations [17,18] the grid-wind farm system is viewed as a two bus system; one at which the WTGU is connected and the other being the infinite bus. The use of probabilistic measures to characterize the impact of WTGU on distribution networks in a steady state context has been suggested in refs. [19,20]. The probabilistic analysis carried out in ref. [21] obtains the probability distribution function (PDF) of node voltages considering a simple gaussian distribution for the load and wind speed variations. In ref. [22] in order to account for the probabilistic variation of load, wind speed as well as other generation, a sequence of steady state load flow solutions (using mean values of the variables) is obtained. From these load flow solution results, the PDF of node voltages are obtained. In both these studies only fixed speed WTGU are considered and approximate models for the WTGU have been used.

It is seen that efforts to understand the steady state interaction of the grid-WTGU systems have been scanty. Even in the deterministic investigations where this issue is considered [14–17], only a simple induction generator equivalent circuit has been used to model the WTGU. However, the power output of the wind generator depends on the turbine characteristics as well as the control characteristics of the power controllers (when they are present). These features of the WTGU have not been considered in any of the above studies. In ref. [18] an approximate turbine characteristics has been used for modelling the fixed speed type of WTGU alone. However, there are three other types of WTGU (semi-variable speed, doubly fed induction generator and generator with front end converter) and so far no attempt has been made to model them for steady state studies. Further, none of the above investigations attempt to study the manner in which the performance of the WTGU is affected by the varying grid conditions. Probabilistic load flow schemes used in refs. [21,22] also make use of only simple WTGU models.

The paper is concerned with the steady behavior of WTGU-grid systems, in particular the impact of WTGU used as DG sources. As mentioned earlier, the WTGU are connected to the grid at both transmission and distribution voltage level. For studies on transmission systems connected to wind farms, an aggregated model of the wind farm is considered to be adequate [24]. In a wind farm supervisory controls are generally present [26]. These controls essentially determine the active power and reactive power supplied by the wind farm at the point of common connection (PCC). These features rather than the individual WTGU characteristics have to be considered while developing models for wind farms. Modelling such wind farms is not considered here.

A WTGU when used as a DG source operates as a part of small primary distribution system. There is a need to understand how various WTGU perform when they are connected to the power grid at this voltage level. Further the primary distribution systems are traditionally designed to operate with the power flowing only in one direction. With the inclusion of these WTGU sources, this characteristic of the distribution system changes and hence, the impact of this change on the system needs to be studied.

The aim of the present investigation is to study the steady state behavior of WTGU as DG sources and their impact on the distribution network. In view of this, the paper addresses the following:

1. Identify the features of different types of WTGU which affect their steady state behavior.
2. Develop models for each type of WTGU that facilitate the computation of the steady state power outputs.
3. Analyze the impact of wind speed and terminal voltage variations on the steady state behavior of the individual WTGU.
4. Illustrate the application of the new WTGU models for obtaining the steady state load flow solution of a radial distribution feeder having distributed wind generation, assuming the wind speed at the instant of interest is given/known.
5. Study the impact of wind based DG on the operation of radial systems.

2. Models for WTGU

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. 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. The power output of some of the WTGU is not regulated and in others where it is regulated, the control characteristics are different. Hence, model for each type of WTGU has been developed.

2.1. Fixed speed WTGU

This type of WTGU has a squirrel cage induction generator which is driven by a wind turbine either having a fixed turbine blade angle (stall regulated fixed speed WTGU) [23] or having a pitch controller to regulate the blade angle (pitch regulated fixed speed WTGU). In both these types of WTGU, the induction generator is directly connected to the grid. In the operating range the rotor speed varies within a very small range (around 5% of the nominal value) and hence, these are reckoned as fixed speed WTGU. Normally in these WTGU a fixed shunt capacitor is used to provide reactive power compensation.

2.1.1. Stall regulated fixed speed WTGU

The power output of this class of WTGU depends on the turbine and generator characteristics, wind speed, rotor speed and the terminal voltage. For a given turbine and generator characteristics, wind speed alone is the independent variable while the rotor speed and terminal voltage are interdependent and vary

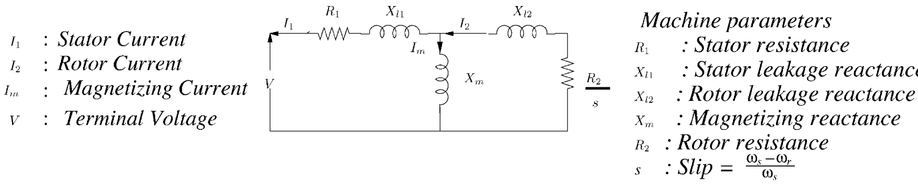

Fig. 1. Induction machine equivalent circuit.

with wind speed as well as the network conditions. In some of the existing models for this WTGU, either the turbine characteristics is neglected [14–17] (constant mechanical input) or the WTGU power output is considered to be independent of the terminal voltage variation [21]. The method suggested here facilitates the computation of the power output of the WTGU without making these simplifying assumptions.

In order to take this interdependency of rotor speed and voltage into account, the power output is calculated iteratively. For a given wind speed, the power output is computed for an assumed terminal voltage. The calculation is repeated if the computed power output results in a change in the terminal voltage. The power output calculation requires finding the rotor speed common to both the turbine and the generator. This rotor speed corresponds to the intersection of the turbine and the generator characteristics. Since the two characteristics are non-linear, an iterative method has been developed here for computing the rotor speed.

The passive stall regulated wind turbines [23] have their rotor blades bolted onto the hub at a fixed pitch angle (ν). The wind turbine mechanical power output is a function of rotor speed as well as the wind speed [23] and is expressed as,

$$P_{\mathrm{m}}(u_{\mathrm{w}}, \omega_{\mathrm{r}}) = \tfrac{1}{2}\rho A u_{\mathrm{w}}^{3} C_{\mathrm{p}}(\lambda, \nu) \tag{1}$$

where A is the area swept by the rotor, ρ the density of air, u_{w} the wind speed and $C_{\mathrm{p}}(\lambda, \nu)$ is the power coefficient. The power coefficient is a nonlinear function of the tip speed ratio λ and the pitch angle ν. The tip speed ratio depends on the wind and rotor speed and is given as

$$\lambda = \frac{\omega_{\mathrm{r}}\eta R}{u_{\mathrm{w}}} \tag{2}$$

where ω_{r} is the generator rotor angular speed, η the gear ratio and R is the rotor radius at the turbine blades (turbine swept region). The power coefficient curve ($C_{\mathrm{p}}(\lambda, \nu)$ versus λ) is obtained experimentally (it varies across the size and make) and is provided by the manufacturer. The experimental curve provided by the manufacturer gives variation of C_{p} with respect to λ for the ν of the turbine. For our calculation here, we need to get C_{p} as a function of u_{w} and ω_{r}. This is obtained as follows. It is shown in ref. [23] that there is a high degree of similarity seen in the power coefficient curves obtained for various stall regulated wind turbines in use. In view of this a general functional form for C_{p} has been suggested, which can be used to represent the rotor power coefficient of a given turbine, by proper choice of constants. This general functional representation (3) for $C_{\mathrm{p}}(u_{\mathrm{w}}, \omega_{\mathrm{r}}, \nu)$ is

$$C_{\mathrm{p}}(u_{\mathrm{w}}, \omega_{\mathrm{r}}, \nu) = c_1\left(c_2\frac{1}{\Lambda} - c_3\nu - c_4\nu^{x} - c_5\right)\exp\frac{-c_6}{\Lambda} \tag{3}$$

where $1/\Lambda = 1/(\lambda + 0.08\nu) - 0.035/(1+\nu^3)$ and c_1 to c_6 and x are constants.

The constants (c_1 to c_6 and x) are computed using the procedure in ref. [23] for the given characteristics of the particular turbine (size, model, make and site) under consideration. Hence, given the experimental power coefficient curve, an analytical expression for the power curve (P_{m} versus ω_{r}) of the turbine can be obtained using (1) and (3) for the given pitch angle ν and any particular wind speed u_{w}.

The induction generator output in terms of ω_{r} and V the terminal voltage, is obtained by using the equivalent circuit of the induction machine. From the equivalent circuit shown in Fig. 1, the expression for air gap power is obtained as:

$$P_{\mathrm{g}}(V, \omega_{\mathrm{r}}) = |I_2|^2 R_2 \frac{1-s}{s} \tag{4}$$

where the rotor current I_2 is,

$$I_2 = \frac{V((R_2/s) + jX_{l2} + jX_{\mathrm{m}})(R_1 + jX_{l1} + jX_{\mathrm{m}})}{jX_{\mathrm{m}}[((R_2/s) + jX_{l2})(jX_{\mathrm{m}}) + ((R_2/s) + jX_{l2} + jX_{\mathrm{m}})(R_1 + jX_{l1})]} + \frac{V}{jX_{\mathrm{m}}} \tag{5}$$

For a given wind speed and terminal voltage, the rotor speed is determined by equating the mechanical power input and the developed electrical power. Once the rotor speed is determined, the electrical power output can be computed.

Algorithm 1. Stall regulated fixed speed WTGU power output (Pe and Qe). Given wind speed u_{w} and the terminal voltage V

1. Initialize the rotor speed ω_{r}

If $u_{\mathrm{w}} < u_{\mathrm{w\,nominal}}$

$$s = s_{\mathrm{rated}}\frac{u_{\mathrm{w}} - u_{\mathrm{w_{cut\text{-}in}}}}{u_{\mathrm{w_{nominal}}} - u_{\mathrm{w_{cut\text{-}in}}}} \tag{6}$$

where s_{rated} is the slip corresponding to the rated speed of the generator and $u_{\mathrm{w_{nominal}}}$, $u_{\mathrm{w_{cut\text{-}in}}}$ are the nominal and cut-in wind speeds, respectively.

Else

$$s = s_{\mathrm{rated}}$$

$$\omega_{\mathrm{r}} = \omega_{\mathrm{s}}(1 - s)$$

2. Compute the accelerating power

$$P_a = P_g(V, \omega_r) - P_m(u_w, \omega_r) \quad (7)$$

where $P_g(V, \omega_r)$ is the air gap power (4) and $P_m(u_w, \omega_r)$ is the mechanical power input (1) with $C_p(\lambda, \nu)$ of (1) being replaced by (3)

3. If $P_a = 0$

(a) Go to Step 4

Else

(a) Solve the non-linear Eq. (7) iteratively, setting $P_a = 0$, to obtain the rotor speed ω_r

4. Compute I_1 from the equivalent circuit shown in Fig. 1.
5. Compute real and reactive power output of the WTGU using

$$\text{Pe} = \Re(VI_1^*) \quad (8)$$

$$\text{Qe} = \Im(VI_1^*) \quad (9)$$

It must be noted here that the above method differs from a similar method proposed in ref. [18] in two important aspects. First, the method in ref. [18] is essentially a trial and error process; starting with an assumed ω_r the generator power output is calculated. If this does not match with P_m, ω_r is updated based only on the approximate sensitivity of Pe with respect to ω_r. Here, the values of ω_r is obtained as the solution of a single nonlinear Eq. (7). The second difference is that the two methods differ in the computation of the mechanical power P_m. In ref. [18], for obtaining P_m, first the $C_p(\lambda, \nu)$ is derived through some assumptions from the power curve of the WTGU (Pe versus ω_r) and using this $C_p(\lambda, \nu)$ in (1) P_m is computed. In the algorithm proposed here, we use the actual $C_p(\lambda, \nu)$ curve for computing P_m and no assumptions are made in this computation. Moreover, a new scheme has been suggested to obtain a good initial value for the rotor speed (ω_r). With this as the initial start, the proposed algorithm converges in about two to three iterations, corresponding to an error of less than 10 W in P_a.

2.1.2. *Pitch regulated fixed speed WTGU*

In this class of WTGU, the pitch angle controller regulates the wind turbine blade angle (ν) according to the wind speed variations. Hence, the power output of this class of WTGU depends on the characteristics of the pitch controller in addition to the turbine and generator characteristics. Since the interest here is in steady state behavior, rather than the actual control process the effect of the control process is important. This control guarantees that the power output of the WTGU for any wind speed will be equal to the designed value for that speed (irrespective of the voltage). 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 Pe known and an assumed voltage, the induction generator Pe expression can be recast as a quadratic equation in slip (rotor speed). This equation is solved to get the slip value. With the slip known, the reactive power output Qe is calculated from the induction generator equivalent circuit. Any change in voltage due to these output changes are computed and the above process is repeated till convergence.

Algorithm 2. Pitch regulated fixed speed WTGU power output (Pe and Qe)

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. Pe of the induction generator is given by

$$\text{Pe} = \frac{[R_1(R_2^2 + s^2(X_m + X_{l2})^2) + sR_2X_m^2]|V|^2}{[R_2R_1 + s(X_m^2 - (X_m + X_{l2})(X_m + X_{l1}))]^2 + [R_2(X_m + X_{l1}) + sR_1(X_m + X_{l2})]^2} \quad (10)$$

Knowing Pe and all the other parameters of the induction generator, (10) can be written as a quadratic equation in s as follows

$$as^2 + bs + c = 0 \quad (11)$$

where,

$$a = \text{Pe}R_1^2(X_{l2} + X_m)^2 + \text{Pe}(X_mX_{l2} + X_{l1}(X_{l2} + X_m))^2 - |V|^2R_1(X_{l2} + X_m)^2,$$

$$b = 2\text{Pe}R_1R_2X_m^2 - |V|^2R_2X_m^2$$

and

$$c = \text{Pe}R_2^2(X_{l1} + X_m)^2 + \text{Pe}(R_2R_1)^2 - |V|^2R_1R_2^2.$$

Then the slip is given by

$$s = \min\left|\frac{-b \pm \sqrt{b^2 - 4ac}}{2a}\right| \quad (12)$$

where a, b and c are as defined in (11).

3. Knowing s compute Qe as

$$\text{Qe} = \frac{[X_mX_{l2}s^2(X_m + X_{l2}) + X_{l1}s^2(X_m + X_{l2})^2 + R_2^2(X_m + X_{l1}))]|V|^2}{[R_2R_1 + s(X_m^2 - (X_m + X_{l2})(X_m + X_{l1}))]^2 + [R_2(X_m + X_{l1}) + sR_1(X_m + X_{l2})]^2} \quad (13)$$

2.2. *Semi variable speed WTGU*

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. Power electronic devices are used to vary the rotor resistance. In these WTGU, the reactive power compensation is normally provided by a fixed shunt capacitor. There are two controllers, a

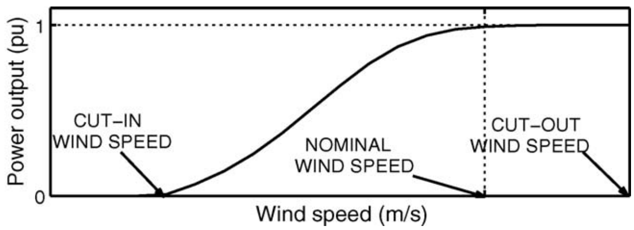

Fig. 2. Typical power curve: semi-variable speed WTGU.

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 output versus wind speed characteristics. A typical power curve is shown in Fig. 2.

Determination of the output of this WTGU for a given wind speed and assumed/known terminal voltage involves the computation of Pe and Qe. The Pe computation is straight forward as the WTGU power characteristic readily provides this value. However, computation of Qe is tricky. This is because as compared to the pitch controlled WTGU discussed in Section 2.1.2, in this case in addition to the slip, the rotor resistance is also determined by the controller and hence is unknown. This difficulty is overcome by noting a very interesting feature of the expression for Pe and Qe of the induction generator. We note that the expression for Pe (10) and Qe (13) can be recast as a quadratic function of a new variable R_2/s. Hence, even when R_2 and s are unknown the quantity R_2/s (say $R_{\rm eq}$) can be computed by solving the quadratic equation in $R_{\rm eq}$ involving Pe. To compute Qe, this value of $R_{\rm eq}$ is used in the modified expression for Qe. The quadratic equation for $R_{\rm eq}$ can be derived from (10) and is as follows:

$$aR_{\rm eq}^2 + bR_{\rm eq} + c = 0 \tag{14}$$

where,

$$a = \mathrm{Pe}(R_1^2 + (X_{l1} + X_{\rm m})^2) - |V|^2 R_1^2,$$

$$b = 2R_1 \mathrm{Pe} X_{\rm m}^2 - X_{\rm m}^2 |V|^2$$

and

$$c = \mathrm{Pe}(R_1)^2 (X_{l2} + X_{\rm m})^2 + \mathrm{Pe}(X_{\rm m}^2 - (X_{\rm m} + X_{l2})(X_{\rm m} + X_{l1}))^2 - R_1(X_{\rm m} + X_{l2})^2 |V|^2.$$

Algorithm 3. Semi-variable speed WTGU power output (Pe and Qe). Given wind speed $u_{\rm w}$ and the terminal voltage V

1. For the given $u_{\rm w}$ obtain Pe from the power curve of the WTGU (provided by the manufacturer similar to Fig. 2).
2. Compute $R_{\rm eq}$ by solving (14) as

$$R_{\rm eq} = \min\left|\frac{-b \pm \sqrt{b^2 - 4ac}}{2a}\right| \tag{15}$$

where a, b and c are as defined in (14).

3. Knowing $R_{\rm eq}$, compute Qe as

$$\mathrm{Qe} = \frac{[R_{\rm eq}^2(X_{\rm m} + X_{l1}) - (X_{\rm m} + X_{l2}) \times (X_{\rm m}^2 - (X_{\rm m} + X_{l2})(X_{\rm m} + X_{l1}))]|V|^2}{[R_{\rm eq}R_1 + (X_{\rm m}^2 - (X_{\rm m} + X_{l2})(X_{\rm m} + X_{l1}))]^2 + [R_{\rm eq}(X_{\rm m} + X_{l1}) + R_1(X_{\rm m} + X_{l2})]^2} \tag{16}$$

2.3. Variable speed WTGU

The following are the two major categories of this class of WTGU:

1. WTGU having double fed induction generator (DFIG): The DFIG consists of a pitch controlled wind turbine and an induction generator whose stator winding is directly connected to the grid but the rotor circuit is connected to the grid through a back to back voltage source converter. The voltage source converter (connected to the rotor) applies voltage across the rotor which is regulated by two rotor current controllers.
2. WTGU having generator (synchronous/induction) with front end converter (GFEC): The GFEC consists of a pitch controlled wind turbine and a variable frequency synchronous or induction generator connected to the grid through a power electronic converter (back to back voltage source converter). In this case, the voltage source converter output applied to the stator is varied by the control signals obtained from the current controllers.

In both the schemes (DFIG and GFEC) in addition to the two current controllers (d- and q-axis) there are two power controllers (active and reactive). The current controllers are very fast and they regulate the q and d components of machine currents to reference values that are generated by the relatively slow power controllers. The reference value specified by the active power controller ensures that maximum power is extracted below nominal wind speed. However, above nominal wind speed the pitch angle controller operates so that rated power output is maintained. The reference value generated by the reactive power controller ensures that the reactive power output is equal to the specified value when it is operating with specified Q. Alternately, some of the WTGS may be equipped with a power factor controller. This controller maintains a constant power factor (settable by the user, with in limits) at all wind speeds by appropriately varying the reference setting of the reactive power controller.

In both these types of variable speed WTGU the range of possible Pe and Qe output may also be limited as the current controllers have limiters that restrict the range of possible I_d (reactive component of current) and I_q (active component of current). In addition to this, the magnitude of total current (vector sum of I_d and I_q) cannot exceed the maximum current rating of the generator. Generally, these WTGU are designed so that none of these limits are violated (with power factor control) in the normal operating conditions. The normal operating range of voltages is specified by the manufacturer and for the units in operation this range is quite large (generally ±10% of the nominal voltage). Since this range is quiet large, in many cases it may not be necessary to consider the current limits. Hence, an algorithm for the normal operating condition, with out considering the limits, has been given below. However, if the terminal voltage is outside the specified normal operating range then it is necessary to consider several issues. These issues are discussed in Section 2.3.1 and a model for the variable speed WTGU during the abnormal operating conditions has been proposed (Algorithm 4a).

The Algorithm 4 proposed here (for normal operating conditions) first obtains Pe for a given wind speed, from the power curve which is normally provided by the manufacturer. The Qe output of these variable speed WTGU corresponds to the specified/set value (if Qe is specified). If power factor is specified then Qe is computed so that at this Pe the power factor corresponds to the specified value. Generally these WTGU are designed to operate at unity power factor or with Qe = 0, under normal operating condition.

Algorithm 4. Variable speed WTGU power output (Pe and Qe).

Given wind speed and terminal voltage V

1. For the given wind speed, obtain Pe from the power curve (normally provided by the manufacturer).
2. If Qe is specified,
   $\mathrm{Qe} = \mathrm{Qe}_{\mathrm{specified}}$
   Else if power factor ($\cos\varphi$) is specified,

$$\mathrm{Qe} = \mathrm{Pe}\sqrt{\frac{1-\cos^2\phi}{\cos\phi}}$$

2.3.1. Variable speed WTGU model: abnormal voltage conditions

Distribution networks in many developing countries operate with a poor voltage regulation. The voltages could sometimes be well beyond the normal range (generally between 0.9 and 1.1 pu) specified by the WTGU manufacturer. In such situations the open loop controls (which are mainly device protective controls) of the WTGU operate. The operation of these open loop controls causes the machine to trip in the case of fixed speed WTGU (pitch as well as stall regulated) and semi-variable speed WTGU. However, in the case of variable speed WTGU the machine continues to operate but its operation is dictated by the open loop controls [26].

When the terminal voltage of the variable speed WTGU is beyond the normal range, the open loop controls (depending on its settings) modify the current references generated by the closed loop power controllers and hence determine the power output of these machines. While simulating such systems, a different procedure, which takes into account the operation of the open loop controls has to be used to compute their output. These open loop controls ensure that each component of the current as well as the total current do not exceed their maximum limits. Thus in order to model this behavior, in the simulation model one must calculate each component of current as well as the total current and check for the limit violations. If there are any violations the corresponding currents are reset to their appropriate limit values and Pe as well as Qe are recomputed. However, the manner in which these current limit violations could affect Pe and Qe depends on the specific type of implementation. In some of the implementations (Type-1) like the GE variable speed DFIG WTGU [26], when the specified Pe and Qe cannot be met due to the maximum limit violation of the total current, maintaining the Qe output is given a higher priority. Thus Pe is reduced so as to maintain the specified Qe. Hence, in this case it is necessary to check for d-axis as well as total current limit violations. While in the other implementations of variable speed WTGU [31] (Type-2), the limits for d-axis as well as q-axis currents automatically take care of the total maximum current limit. Thus in this case it is sufficient to check for d as well as q-axis current limit violations. A general algorithm applicable for these two types of variable speed WTGU has been given below.

A similar algorithm can be used for GFEC type of variable speed WTGU. The algorithm given here is for a particular type of DFIG which uses stator flux rotating frame of reference. This algorithm can also be used for other types of DFIG or other types of variable speed WTGU by suitably modifying the equations used to calculate the Pe and Qe as well as the currents.

Algorithm 4a. Variable speed WTGU power output (Pe and Qe) when the terminal voltage of the WTGU is beyond the specified nominal range

For a given wind speed and terminal voltage V,

1. For the given wind speed, obtain Pe from the power curve (normally provided by the manufacturer).
2. If Qe is specified

(a) Set $\mathrm{Qe} = \mathrm{Qe}_{\mathrm{specified}}$

Else, if power factor ($\cos\varphi$) is specified,

(a) $\mathrm{Qe} = \mathrm{Pe}\frac{\sqrt{1-\cos^2\phi}}{\cos\phi}$

3. For this Qe compute I_{2d} using

$$I_{2d} = \frac{|V|}{X_\mathrm{m}} - \frac{2\mathrm{Qe}(X_{l1}+X_\mathrm{m})}{3|V|X_\mathrm{m}} \tag{17}$$

4. If I_{2d} is greater than its maximum limit

(a) Set I_{2d} to its maximum limit.
(b) Recompute Qe as

$$\mathrm{Qe} = \frac{3}{2}|V|\frac{X_\mathrm{m}}{X_{l1}+X_\mathrm{m}}\left(\frac{|V|}{X_\mathrm{m}} - I_{2d}\right) \tag{18}$$

Else, if I_{2d} is less than its minimum limit

(a) Set I_{2d} to its minimum limit.
(b) Recompute Qe using (18).

5. If it is Type-1 variable speed WTGU then

(a) Compute I_{2d} using (17), I_{2q} using (19) and I_2 using (20)

$$I_{2q} = \frac{2\mathrm{Pe}(X_{l1} + X_{\mathrm{m}})}{3|V|X_{\mathrm{m}}} \tag{19}$$

$$I_2 = \sqrt{I_{2q}^2 + I_{2q}^2} \tag{20}$$

(b) If I_2 is greater than the maximum current limit

i. Set it to its maximum value.
ii. For this value of I_2, with I_{2d} unchanged, recalculate I_{2q} as $I_{2q} = \sqrt{I_2^2 - I_{2d}^2}$.
iii. Using this value of I_{2q}, recompute Pe

$$\mathrm{Pe} = -\frac{3}{2}|V|\frac{X_{\mathrm{m}}}{X_{l1} + X_{\mathrm{m}}} I_{2q} \tag{21}$$

Else if it is Type-2 variable speed WTGU then

(a) Compute I_{2q} using (19).
(b) If I_{2q} is greater than its maximum limit

i. Set I_{2q} to its maximum value.
ii. For this value of I_{2q}, recompute Pe using (21).

The low rather than high voltage condition is experienced most often on a distribution system. During the abnormal low voltage condition the terminal voltage at the WTGU bus is generally lower than 0.9 pu. When this happens in order to inject the same amount of reactive power Qe (at a reduced voltage), I_{2q} increases. Consequently, at reduced voltages the probability of I_{2q} tending to violate its maximum limit is very high. On the other hand, in the case of Type-1 variable speed WTGU the chances of I_2 exceeding its maximum limit depends on the terminal voltage magnitude as well as the wind speed. When the wind speed is beyond or close to the nominal wind speed I_{2q} is very high. In such a situation if the voltage at the WTGU terminals is low, then I_{2q} is also very high. Thus there is a very high probability of I_2 tending to violate its limit. In such a situation as I_{2q} is decreased to force limit compliance, Pe decreases.

3. Load flow analysis including WTGU

Load flow analysis is the primary tool for assessing the operation of the systems in steady state. As the focus of this paper is limited to the use of WTGU as DGs, the systems of interest would be the primary distribution systems. These systems are mostly radial. Inclusion of these WTGU into these systems results in the increase in the number of buses where power is fed into such systems. However, this does not require that the WTGU buses be treated as voltage specified buses (*PV* buses) because none of the WTGU types have enough reactive power capability to hold their terminal voltage at a specified value. The WTGU buses can be treated as only *PQ* buses (with *P* and *Q* varying across iterations in contrast to a conventional *PQ* bus where they remain constant). Hence, we propose the use of radial load flow method for obtaining the load flow solutions of these systems.

As indicated earlier, for systems having wind generations both types of load flow analysis, i.e., deterministic as well as probabilistic have been used. Here we indicate how the proposed WTGU models can be used in both types of load flow analysis.

3.1. Load flow analysis considering fixed wind speed

In situations where the wind speed at all WTGU are specified and the loads at buses are known, a radial load flow algorithm can provide the solution with very little computation. In this algorithm it is necessary to determine the real and reactive current injection at all the buses. In each iteration at the beginning, the power output of each of the WTGU for the given wind speed and terminal voltage (voltage value obtained in the previous iteration) is obtained using one of the proposed algorithms depending on the type of WTGU. Knowing, the power output the complex current injections are computed at all the nodes. Using these currents and a backward-forward sweep scheme the branch currents are found and voltages at all the buses are updated for this iteration.

3.2. Load flow analysis considering uncertainties

Probabilistic load flow methods are used to analyze and characterize systems with load/generation uncertainties. In the context of systems having wind generation, three such methods have been proposed earlier [21,22]. The method in ref. [21] is applicable in situations where (i) the independent variables (*P*, *Q*) and dependent variables (voltages) can be related through a linear relation around the mean operating point and (ii) all the variations (load, generation) could be considered as normally distributed. In this method, first a deterministic load flow solution is obtained corresponding to the mean value of all independent variables. The WTGU models proposed earlier and the radial load flow scheme discussed above can be made use of for this step. Using the known standard deviations of the independent variables and the known linear relation between the independent and dependent variables (node voltages), the probability distribution of all node voltages are found using convolution [21]. In situations where the assumptions of [21] cannot be made, one can use one of the two methods proposed in ref. [22] for probabilistic load flow analysis. The time series method [22] can be used in situations where the time variation of all the independent random variables are known. The simplified probabilistic method [22] can be used when the PDF of the independent variables are known and some of them are non-gaussian. The solution technique proposed in ref. [22] for both the methods is essentially an enumeration technique. It involves discretisation of the variables/distributions and requires the results of a large number of deterministic load flow solutions. Each such load flow solution gives one sample point for each of the node voltages. Hence, in situations where one of these approaches have to be used, the WTGU models proposed earlier and the deterministic load flow scheme has to be used repeatedly.

4. Simulation study

Two sets of simulation studies have been carried out. The first study aims to understand the operation of grid connected WTGU while the other looks at their impact on the distribution systems. In both these studies, it has been assumed that the wind speed at a wind site at the instant of interest is given/known.

4.1. Operation of grid connected WTGU

In the case of grid connected WTGU both wind speed and terminal voltage are varying. Here the impact of each of these variations on the power outputs of the various types of WTGU have been studied.

4.1.1. WTGU data

The study carried out here considers all the above mentioned types of WTGU, i.e., stall and pitch regulated fixed speed, semi-variable speed and variable speed (DFIG and GFEC) types. The data for the stall regulated fixed speed, semi-variable speed and GFEC types of WTGU are taken from [28]. The data for the pitch regulated type of WTGU is taken from [27] and that for the DFIG is taken from [29].

The stall regulated fixed speed WTGU considered here is the NEG MICON unit of 1 MW capacity. The power coefficient curve $C_p(\lambda, \nu)$ versus λ as provided by the manufacturer is used in ref. [28] to derive the constants (c_1 to c_6) of the analytical expression for the $C_p(u_w, \omega_r, \nu)$ function (3). The constant values c_1 to c_6, pitch angle ν, rotor diameter R and the gear ratio η for this turbine make are: $c_1 = 0.5$, $c_2 = 67.56$, $c_3 = 0$, $c_4 = 0$, $c_5 = 1.517$, $c_6 = 16.286$, $\nu = 5°$, $R = 27$ m and $\eta = 1/67.5$. The air density is taken to be $\rho = 1.225\,\text{kg/m}^3$. For this make and capacity of the stall regulated WTGU, the induction generator circuit parameters are given in Table 1.

The pitch regulated fixed speed WTGU considered here is the Vestas unit of 500 kW rating. The power curve for this WTGU make and capacity is shown in Fig. 3(a). The induction generator circuit parameters for the same unit are given in Table 1. The semi-variable speed WTGU considered here is the Vestas unit of 1 MW rating. The power curve for this WTGU is shown in Fig. 3(b) and the induction generator circuit parameters are given in Table 1.

Table 1
Induction generator circuit parameters

Type of WTGU	Stall regulated fixed speed [28]	Pitch regulated fixed speed [27]	Semi-variable speed [28]
Rating (MW)	1.0	0.50	1.0
Rated (kV)	0.69	0.69	0.69
R_1 (pu)	0.007141	0.005986	0.005671
X_{l1} (pu)	0.21552	0.08212	0.15250
R_2 (pu)	0.00630	0.01690	0.00462
X_{l2} (pu)	0.088216	0.107225	0.096618
X_m (pu)	3.3606	2.5561	2.8985
X_c (pu)	3.3606	2.5561	2.8985

For all these types of WTGU (stall regulated fixed speed, pitch regulated fixed speed and semi-variable speed WTGU), the value of the capacitive reactance (X_c) of the shunt capacitor is taken to be equal to the reactance of the corresponding induction generator magnetizing branch (X_m).

The power curve for the GFEC type of WTGU of 1 MW capacity is shown in Fig. 4(a). The DFIG type of WTGU considered here is the Dewind unit of 1 MW capacity and the power curve of this is shown in Fig. 4(b).

4.1.2. Results: WTGU performance

The results presented here show the variation of Pe and Qe between cut-in and cut-out wind speeds (the WTGU are generally shut down beyond cut-out wind speed). Further, the range of Pe and Qe variation with terminal voltage has been shown by presenting the results for nominal value of voltage (1 pu) and two extreme values of voltage magnitude (0.9 and 1.1 pu). In all the results presented here for the fixed (stall and pitch regulated) as well as semi-variable speed WTGU the shunt capacitor compensation has been included. Hence, the reactive power demand (Qe) refers to the actual reactive power drawn from the grid.

For the stall regulated fixed speed WTGU the variation of Pe with wind speed and for three different terminal voltages is shown in Fig. 5. From this it can be seen that Pe increases with increase in wind speed from cut-in to nominal wind speed and beyond nominal speed it decreases marginally. Further, for a given wind speed even though Pe increases marginally with

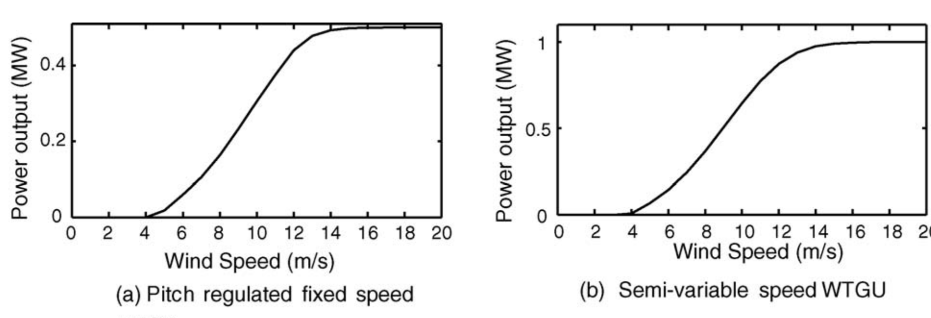

Fig. 3. Power curves of pitch regulated WTGU.

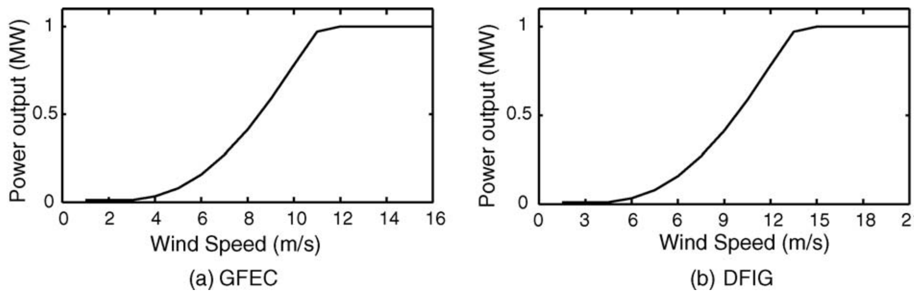

Fig. 4. Power curves of variable speed WTGU.

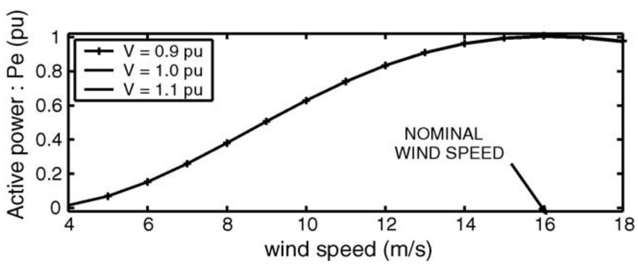

Fig. 5. Variation of Pe: stall regulated fixed speed WTGU.

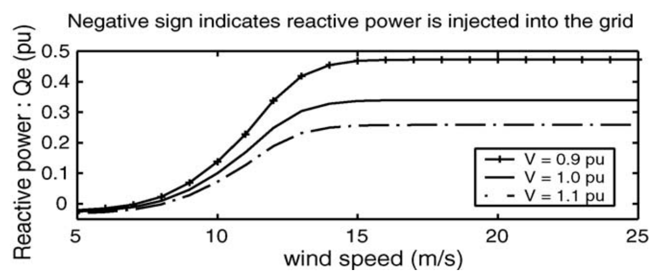

Fig. 7. Variation of Qe: pitch regulated fixed speed WTGU.

increase in voltage, this change is very small (not even seen in the graph of Fig. 5).

Fig. 6 shows the variation of Qe with wind speed at different terminal voltages for the stall regulated fixed speed WTGU. From this it can be seen that the reactive power demand (Qe) increases with increase in wind speed up to the nominal speed and beyond the nominal wind speed it decreases slightly. The terminal voltage variation has a greater impact on Qe as compared to that on Pe. For a given wind speed, increase in terminal voltage decreases the reactive power demand of the stall regulated fixed speed WTGU significantly.

Pe of the pitch regulated fixed speed WTGU is unaffected by the normal range of terminal voltage variations. While Pe varies with wind speed, this variation is in accordance with the power curve of the machine. The reactive power demand Qe of this type of WTGU is affected by both wind speed and terminal voltage variations, as shown in Fig. 7. From this it can be seen that reactive power demand Qe increases with the decrease in terminal voltage. Further, the reactive power demand Qe increases with increase in wind speed up to nominal wind speed. However, beyond nominal wind speed Qe remains constant unlike the behavior seen in the case of the stall regulated fixed speed WTGU.

In the case of semi-variable speed WTGU, terminal voltage variations (normal voltage variation) do not have any impact on the active power output Pe of the generator. However, Pe varies with wind speed and this variation is essentially dictated by the power curve. Unlike Pe, Qe of this type of WTGU is affected by both wind speed and terminal voltage variations and this is shown in Fig. 8. From this it can be seen that the variation of Qe with wind speed is similar to that obtained for the pitch regulated fixed speed WTGU.

For the variable speed type (both GFEC and DFIG) of WTGU, Pe varies with wind speed in accordance to its power curve. Moreover, it is unaffected by the normal range of terminal voltage variations. Further, during the normal operating conditions of these WTGU the specified value (either set by the user or by a power factor controller) of Qe is obtained.

From the above it can be concluded that irrespective of the type of WTGU, at a fixed wind speed, even a fairly wide range of voltage variation (0.9–1.1 pu) does not cause any significant change in Pe. However, the variation of Qe with voltage is not negligible in the case of fixed (stall and pitch regulated) as well as semi-variable speed WTGU. Further, wind speed variation also causes Qe to vary significantly. This is because these systems are generally provided with fixed reactive power compensation

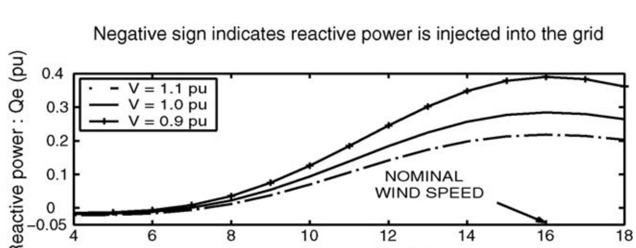

Fig. 6. Variation of Qe: stall regulated fixed speed WTGU.

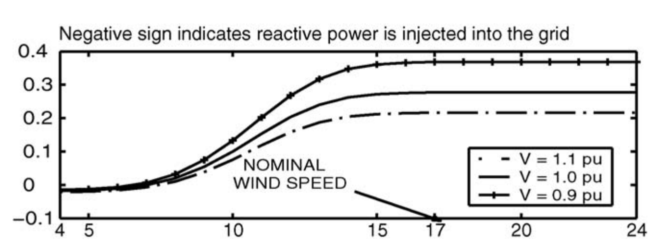

Fig. 8. Variation of Qe: semi-variable speed WTGU.

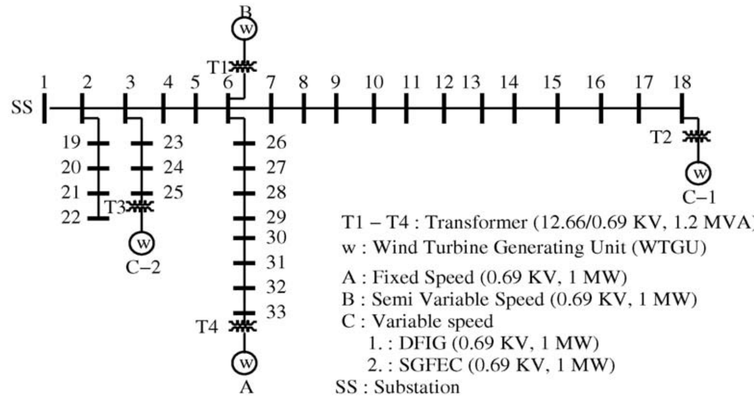

Fig. 9. Modified 33 bus test system.

and for a given terminal voltage the reactive power demand of the WTGU increases with increase in Pe.

4.2. Impact of DG on the distribution network operation

The impact of wind based DG on distribution networks has been assessed through load flow studies, considering a number of operating conditions. For this study, the 33 bus radial distribution system from [30] has been considered.

4.2.1. Test system

The 12.66 kV 33 bus radial distribution test system given in ref. [30] has been slightly modified by introducing four WTGU at four buses. The single line diagram of the modified system is shown in Fig. 9. The modified test system considered here, could be viewed as a typical example of emerging systems; primary distribution system with dispersed generation. The stall regulated fixed speed, semi-variable speed, DFIG and GFEC type of WTGU are connected at different points of the distribution system (Fig. 9) through four transformers (rated 12.66/0.69 kV, 1.2 MVA). The transformer reactance is 0.12 pu (on its own base). Except for the four additional WTGU and transformers, the network and load data are identical to that given in ref. [30] and these details are provided in Appendix A (Table 4). The stall regulated fixed speed, semi-variable speed, DFIG and GFEC type of WTGU considered here are the same ones considered in Section 4.1. The data corresponding to each unit is already given in Section 4.1.1.

4.2.2. Results

Deterministic load flow solutions using radial load flow technique has been obtained for a number of cases. In each case the wind speed at each WTGU is considered to be known and fixed. The following load and wind speed conditions have been considered to study the impact of terminal voltage as well as wind speed variation on the power output of the WTGU and on the distribution network:

Case 1. WTGU operating below cut-in wind speed (which is equivalent to the system without WTGU) and system loads corresponds to the base load [30].

Case 2. WTGU operating at low wind speeds (given in Table 2) with all the variable speed WTGU operating with specified Q ($Qe_{ref} = 0$) and system loads corresponds to the base load.

Table 2
Summary of load flow results at WTGU buses for various load and wind conditions

Case	Bus no.	Type of WTGU	u_w	Pe (MW)	Qe (MVAR)	$\|V\|$ (pu)
1	33	Stall regulated fixed speed	–	0.000000	0.000000	0.878486
	6	Semi-variable speed	–	0.000000	0.000000	0.933139
	18	DFIG	–	0.000000	0.000000	0.895878
	25	GFEC	–	0.000000	0.000000	0.964824
2	33	Stall regulated fixed speed	11	0.748595	0.157656	0.919991
	6	Semi-variable speed	8	0.394330	0.049261	0.958645
	18	DFIG	9.5	0.619500	0.000000	0.958991
	25	GFEC	9	0.586000	0.000000	0.982017
3	33	Stall regulated fixed speed	13	0.890600	0.270924	0.958661
	6	Semi-variable speed	10	0.590918	0.109595	0.975278
	18	DFIG	11	0.929250	0.000000	0.991195
	25	GFEC	10.5	0.879000	0.000000	0.991210
4	33	Stall regulated fixed speed	13	0.892213	0.200400	1.015036
	6	Semi-variable speed	10	0.590918	0.099890	1.012525
	18	DFIG	11	0.929250	0.000000	1.051119
	25	GFEC	10.5	0.879000	0.000000	1.013085

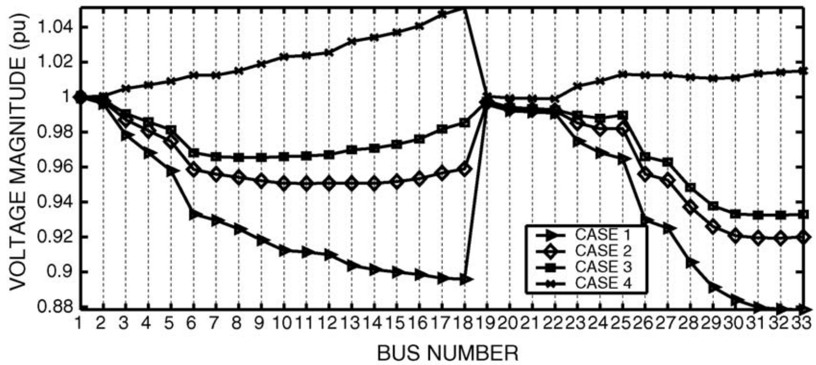

Fig. 10. Voltage profiles of the 33 bus test system.

Case 3. WTGU operating at higher wind speeds than Case 2 (given in Table 2) with GFEC and DFIG operating with settable Q ($Qe_{ref} = 0$) and system loads corresponds to the base load.

Case4. WTGU operating at wind speeds corresponding to Case 3 with GFEC and DFIG operating with settable Q ($Qe_{ref} = 0$) and system load corresponds to 30% of the base load.

In Case 1 the wind speeds are considered to be below cut-in so as represent the system without WTGU. Cases 2–4 correspond to that with WTGU and the wind speeds are considered to be between cut-in and nominal.

The load flow solution has been obtained for all the four cases. For all these cases, the real and reactive power output as well as the voltage magnitude at the WTGU buses obtained at the end of the load flow solution are given in Table 2. In all the results presented here, the reactive power demand at any bus is reckoned as positive (or Qe injected into the bus is negative). Fig. 10 shows the system voltage profile (voltage magnitudes at all the buses) for all the four cases. At the end of the load flow solution the real generation at all the WTGU buses are known and the power fed by the substation (slack bus power) is calculated. The sum of the WTGU generation and the power fed at the slack bus gives the total power input to the system. As the system load is known, the real power loss for each of the cases can be obtained as the difference between the input power and the load. These details for all the four cases are given in Table 3.

4.2.3. Discussion

1. *System voltage profile*: For a given load profile, with increase in the real power output Pe of the WTGU, the voltage magnitude at all the buses increases. From Fig. 10 it can be seen that with increase in the power output of WTGU from zero (Case 1) to around rated values (Case 3) the voltage magnitude at all the buses increases. This increase seen in the voltage magnitude at all the buses of such a system is due to the increase in total Pe (in spite of the increase in reactive power demand of the WTGU) injected by the WTGU. This behavior is easily explained when once it is noted that the *R*/*X* ratio of the feeder is quite high (around 2). Additionally, from Case 4 in Fig. 10 it can be seen that the voltage magnitude at many of the system buses is higher than that of the slack (substation) bus. This is because in Case 4 the net generation of the WTGU is higher than the total system load. Thus it can be said that for given load profile the system voltage magnitudes increase with increase in the net power injected by the WTGU. Further if the total power output of the WTGU is greater than the total load on the feeder then power is supplied to the grid at the substation bus. Due to this the voltage magnitude at some of the buses of such systems could be higher than that of the substation bus.
2. *System loss*: A comparison of the total system loss obtained for the first three cases (Table 3) shows that the percentage loss decreases with increase in the real power output of the WTGU. However, from Table 3 it can be seen that the percentage loss in Case 4 is high, even though the magnitude of loss is low. In Cases 2 and 3, the WTGU and the grid together supply power to the loads in the system. However, in Case 4 the total power generated by the WTGU is much higher than the total system load. Due to this some power is injected into the grid at the slack bus. In order to investigate this issue further, the system loss was obtained for a fixed load (30% of the base case load) and for various wind speeds. The variation in system loss with wind speed for this load is shown in Fig. 11. From this it is evident that with the feeder load remaining constant, as the total power supplied by the WTGU increases the system loss decreases up to a certain limit and beyond this the loss actually starts increasing.

Table 3
System real power loss details

Case	Total system load (MW)	Total WTGU generation (MW)	Substation input (MW)	Power loss (MW)	Loss (%)
1	4.715	0.0	5.0842	0.3692	7.83
2	4.715	2.3484	2.5346	0.1680	3.56
3	4.715	3.2898	1.5754	0.1502	3.18
4	1.4145	3.2914	−1.7776	0.0993	7.02

Table 4
Network and load data of the 33 bus test system

Br. no.	Rc. Nd.	Sn. Nd.	Branch r (Ω)	Parm. X (Ω)	Sending PL (kW)	Node QL (kvar)	Br. no.	Rc. Nd.	Sn. Nd.	Branch r (Ω)	Parm. X (Ω)	Sending PL (kW)	Node QL (kvar)
1	1	2	0.0922	0.0470	100	60	17	17	18	0.7320	0.5740	90	40
2	2	3	0.4930	0.2511	90	40	18	2	19	0.1640	0.1565	90	40
3	3	4	0.3660	0.1864	120	80	19	19	20	1.5042	1.3554	90	40
4	4	5	0.3811	0.1941	60	30	20	20	21	0.4095	0.4784	90	40
5	5	6	0.8190	0.7070	60	20	21	21	22	0.7089	0.9373	90	40
6	6	7	0.1872	0.6188	200	100	22	3	23	0.4512	0.3083	90	50
7	7	8	0.7114	0.2351	200	100	23	23	24	0.8980	0.7091	420	200
8	8	9	1.0300	0.7400	60	20	24	24	25	0.8960	0.7011	420	200
9	9	10	1.0440	0.7400	60	20	25	6	26	0.2030	0.1034	60	25
10	10	11	0.1966	0.0650	45	30	26	26	27	0.2842	0.1447	60	25
11	11	12	0.3744	0.1238	60	35	27	27	28	1.0590	0.9337	60	20
12	12	13	1.4680	1.1550	60	35	28	28	29	0.8042	0.7006	120	70
13	13	14	0.5416	0.7129	120	80	29	29	30	0.5075	0.2585	1200	600
14	14	15	0.5910	0.5260	60	10	30	30	31	0.9744	0.9630	150	70
15	15	16	0.7463	0.5450	60	20	31	31	32	0.3105	0.3619	210	100
16	16	17	1.2890	1.7210	60	20	32	32	33	0.3410	0.5302	60	40

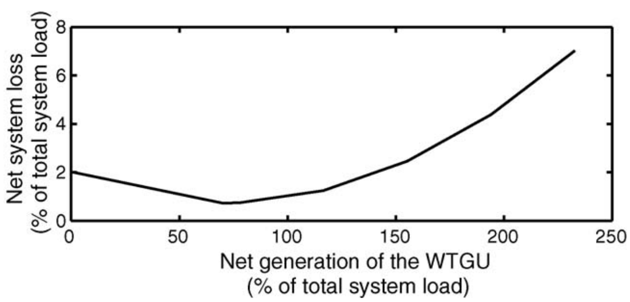

Fig. 11. Variation of the total system loss.

5. Conclusion

In this paper steady state models of various types of WTGU have been developed and their application for both deterministic as well as probabilistic load flow analysis has been demonstrated. These models have been used to assess the steady state behavior of the various WTGU types, under varying system conditions. In addition, simulation studies have been carried out on a radial distribution system having WTGU operating as DG sources.

This study brings out some interesting features about the WTGU performance and their impact when used as DG sources. The real power output of all the types of WTGU (considered here) at any given wind speed does not change perceptibly even with significant changes in terminal voltage. The Q demand of the fixed and semi-variable speed WTGU is sensitive to terminal voltage variations. However, in the case of variable speed WTGU the terminal voltage variation (normal range) has no impact on their Q demand.

Integration of DG to the grid at the distribution voltage levels seems to be beneficial. At this voltage level the network R/X ratios are generally high. In such situations the network voltage profiles improve with increase in generation. The increase in wind generator Q demand with increase in real generation does not seem to have any negative impact on the system voltage profile. Finally, DG helps to reduce the distribution system real power losses.

Appendix A. 33 bus test system data

The data of this test system is taken from [30]. The feeder voltage is 12.66 kV. The base case total system load is 4.715 MW and 2.3 MVAR. The other load and network details of the test system are given in Table 4.

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