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Impact of Different PQ Models of Wind Turbine Generating Units (WTGUs) on System Voltage Performance

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Abstract:
This paper presents the voltage performance analysis of the system with various types of wind turbine generating units (WTGUs). A detailed voltage performance analysis is carried out by considering the different PQ models used for computing the reactive power output of the WTGUs (fixed/semi-variable speed and variable speed WTGUs). The different PQ models of fixed/semi-variable speed WTGUs incorporated for the studies are voltage dependent model, voltage independent model, power factor based model, and PX model. In addition, the variable speed WTGUs are also considered in different fixed power factor mode of operation. Based on these models, a comparative analysis is presented. A modified 27-bus equivalent distribution test system with dispersed wind generation is considered for the studies. Further, the case studies have been carried out by considering the various wind power output levels of WTGUs to examine its impact on system voltage performance. From the comparative analysis, the power factor based model can be the best choice over the other models (which are based on voltages) for the system studies with fixed/semi-variable speed WTGUs.

Keywords: wind farms, WTGUs, grid operation, power flow analysis, comparative analysis, PQ models

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1 Introduction

In the recent years, wind energy has emerged as one of the most successful renewable energy sector in many countries and fastest growing renewable energy technology for generating the power amongst various renewable energy sources. Due to environmental concern and other factors, the share of wind power in relation to the overall installed capacity has increased significantly [1].

As wind energy installations is rapidly growing worldwide, the system operators are more concern about the planning and operation of the system with wind farms. The integration of wind farms with power systems is taking place at both the transmission and distribution voltage levels. Several integration issues are also reported in the literature [2, 3]. The performance of grid connected wind turbine generating units could be quite different from the one that is operating in isolation (at nominal voltage and frequency). This is because the grid voltage and frequency fluctuate around the nominal value. Hence, it is necessary to study the impact performance of the WTGUs when connected to the grid to ensure the secure and reliable operation of the systems.

Therefore, it is important to carry out power flow analysis to address the issues associated with the integration of WTGUs/wind farms with power systems.

In the literature [4–12], the mathematical modeling of various types of wind generators have been developed. The different models of WTGUs also have been proposed to address the interaction between the grid and WTGUs in the steady state context.

Divya and Rao [7] propose PQ based models of various types of fixed/semi-variable speed WTGUs based on a steady state model of the induction machine using slip formulation that relates the terminal powers with the speed of the machine. The active power output of WTGUs can be obtained from the power curve supplied by the manufacture. The reactive power output of WTGUs is expressed as a function of the induction generator circuit parameters, slip (rotor speed), and terminal voltage from the complete equivalent circuit of the induction machine.

However, the studies were carried out by considering the variable speed wind turbine generating units (VS-WTGUs) in unity power factor (UPF) mode of operation only. Especially, the leading power factor (induc-

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tive) mode of operation of VS-WTGUs has strong impact on the system voltage performance, which is not discussed/analyzed in the literature.

Based on these models, researchers in the past have investigated the impact of WTGUs on various system aspects [13, 14] particularly the voltage stability analysis of the system under steady state as well as transient conditions.

This paper presents the voltage performance analysis of the system with various types of WTGUs. This study is extended for the different PQ models used for computing the reactive power output of the WTGUs. The different PQ models of fixed/semi-variable speed WTGUs incorporated for the studies are voltage dependent model, voltage independent model, power factor based model, and PX model. The voltage dependent and independent models are based on the complete equivalent representation of the induction machine. Further, the voltage dependent model is also considered in compensated and uncompensated cases.

In addition, the VS-WTGUs are considered in different fixed power factor mode of operation, that is, UPF or 0.95 lagging/leading power factor. Based on these models, a comparative analysis is carried out to assess the impact of wind generation on distribution system voltage performance. In this study, a sequential load flow solution approach is used to obtain an operating point of power systems with WTGUs. The power flow injection method is used to include PQ models of WTGUs into power flow formulation. Then, it is solved by using Newton-Raphson iterative method to obtain the voltage profile of the system. A modified 27-bus equivalent distribution test system with dispersed wind generation is considered for the studies. Further, the case studies have been carried out by considering the various power output levels of WTGUs (both fixed/semi-variable and variable speed wind generators) with adapting the power factor based model for fixed/semi-variable speed WTGUs, and fixed power factor mode of operation for VS-WTGUs to examine its impact on system steady state voltage performance.

2 Mathematical modeling and power output calculation of WTGUs

The most of the WTGUs use induction generator, some of the basic equations describing steady state behaviour of an induction generator are analyzed using the equivalent circuit representation of the machine. The mathematical modeling of an induction generator is given in Appendix A.

2.1 Fixed speed wind generator

The fixed speed WTGU has a squirrel cage induction generator, which is driven by a wind turbine having either a fixed turbine blade angle (stall regulated fixed speed WTGU) or a pitch controller to regulate the turbine 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 called as fixed speed WTGUs.

2.1.1 Stall regulated fixed speed wind generator (SR-FSWG)

The power output of SR-FSWG 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 with wind speed as well as the network conditions.

In some of the existing models of SR-FSWG, the turbine characteristic is neglected [8, 15], i.e., for a given wind speed, the mechanical input to the generator or turbine output is known from power curve. The interdependency of rotor speed and voltage is not considering in this model.

2.1.2 Algorithm for power output calculation of SR-FSWG

1. For a given wind speed (u_w), obtain the mechanical power input (P_m) from the power curve of WTGU (provided by the manufacturer).

2. Equate the mechanical power (P_m) and the developed electrical power/air gap power (P_{em}) from eq. (30) by neglecting friction and windage losses.

$$P_{em}(V, \omega_r) - P_m = 0 \tag{1}$$

Knowing the termial voltage (V), P_{em}, and other parameters of the induction generator, eq. (1) can be written as a quadratic equation in terms of slip s;

$$as^2 + bs + c = 0 \tag{2}$$

where, $a = P_{em}(X_m(X_{l1} + X_{l2}) + X_{l1}X_{l2})^2 + R_1^2(X_m + X_{l2})^2 - |V|^2X_m^2R_2$
$b = P_{em}(2R_1R_2X_m^2) + |V|^2R_2X_m^2$
$c = P_{em}((R_1R_2)^2 + R_2^2(X_1 + X_m)^2).$
Then, the slip's is given by

$$s = -min\left|\frac{-b \pm \sqrt{b^2 - 4ac}}{2a}\right| \tag{3}$$

where a, b, and c are as defined in eq. (2)

3. Knowing the slip s, compute I_1 using eq. (28).
4. Compute real and reactive power output of the WTGU using

$$P_{WTGU} = \Re\left(VI_1^*\right) \tag{4}$$

$$Q_{WTGU} = \Im\left(VI_1^*\right) \tag{5}$$

2.1.3 Pitch regulated fixed speed wind turbine generator (PR-FSWG)

In pitch regulated fixed speed WTGU, the pitch angle controller regulates the wind turbine blade angle (ν) according to the wind speed variations. The pitch angle controller is generally operational at high wind speeds, when the power output of the WTGU tends to exceed the rated value. However, at wind speeds below nominal the performance of WTGU is similar to the stall regulated fixed speed WTGU.

2.1.4 Algorithm for power output calculation of PR-FSWG

1. For a given wind speed (u_w), obtain P_{WTGU} from the power curve of the WTGU (provided by the manufacturer)
2. The active power (Pe_{IG}) output of the induction generator is given by eq. (33). Knowing the P_{WTGU} (i.e., $P_{WTGU} = Pe_{IG}$), terminal voltage (V), and other parameters of the induction generator, eq. (33) can be rewritten in the form of a quadratic equation in terms of slip s;

$$as^2 + bs + c = 0 \tag{6}$$

where,
$a = P_{WTGU}R_1^2(X_{l2} + X_m)^2 + P_{WTGU}(X_mX_{l2} + X_{l1}(X_{l2} + X_m))^2 - |V|^2R_1(X_{l2} + X_m)^2$
$b = 2P_{WTGU}R_1R_2X_m^2 - |V|^2R_2X_m^2$
$c = P_{WTGU}R_2^2(X_{l1} + X_m)^2 + P_{WTGU}(R_1R_2)^2 - |V|^2R_1R_2^2.$
Then, the slip sis given by

$$s = -min\left|\frac{-b \pm \sqrt{b^2 - 4ac}}{2a}\right| \tag{7}$$

where a, b, and c are as defined in eq. (6)

3. Knowing the slip s, compute I_1 using eq. (28).
4. Compute reactive power output of the WTGU using

$$Q_{WTGU} = \Im\left(VI_1^*\right) \tag{8}$$

2.1.5 Semi-variable speed wind turbine generator (SSWG)

The semi-variable speed 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 circuit is used to vary the rotor resistance. Hence, there are two types of 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 a given wind speed, the active power (P_{WTGU}) output is directly obtained from the power curve provided by the manufacturer while reactive power (Q_{WTGU}) output needs to be computed. The reactive power (Q_{WTGU}) output of the WTGU can be determined if the reactive power (Qe_{IG}) demand of the induction generator is known. However, Qe_{IG} eq. (34) is unknown, and depends on the circuit parameters, terminal voltage and the slip (rotor speed) which is evident from eq. (34). In case of semi-variable speed WTGU, both slip and rotor resistance are unknown. Although the quantity Pe_{IG} eq. (33) is known to be equal to P_{WTGU} (i.e., $Pe_{IG} = P_{WTGU}$) alone is not adequate to compute rotor resistance R_2 and slip (s) independently. This difficulty is overcome by recasting the expression for Pe_{IG} eq. (33) and Qe_{IG} eq. (34) as a function of a single new variable R_{eq} (i.e., $R_{eq} = R_2/s$). The modified equations for both active and reactive power output are given below.

$$Pe_{IG} = \frac{[R_1(R_{eq}^2 + (X_m + X_{l2})^2) + R_{eq}X_m^2]|V|^2}{[R_{eq}R_1 + (X_m^2 - (X_m + X_{l2})(X_m + X_{l1}))]^2 + [R_{eq}(X_m + X_{l1}) + R_1(X_m + X_{l2})]^2} \tag{9}$$

$$Qe_{IG} = \frac{[R_{eq}^2(X_m + X_{l1}) - (X_m + X_{l2})(X_m^2 - (X_m + X_{l2})(X_m + X_{l1}))]|V|^2}{[R_{eq}R_1 + (X_m^2 - (X_m + X_{l2})(X_m + X_{l1}))]^2 + [R_{eq}(X_m + X_{l1}) + R_1(X_m + X_{l2})]^2} \tag{10}$$

2.1.6 Algorithm for power output calculations

1. For a given wind speed (u_w), obtain P_{WTGU} from the power curve of the WTGU (provided by the manufacturer)
2. The active power (Pe_{IG}) output of the induction generator is given by eq. (9).Knowing the P_{WTGU} (i.e., $P_{WTGU} = Pe_{IG}$), terminal voltage (V), and other parameters of the induction generator, eq. (9) can be rewritten in the form of a quadratic equation in terms of R_{eq} as follows

$$aR_{eq}^2 + bR_{eq} + c = 0 \tag{11}$$

   where,
   $a = P_{WTGU}(R_1^2 + (X_{l1} + X_m)^2) - |V|^2R_1$
   $b = 2P_{WTGU}R_1X_m^2 - |V|^2X_m^2$
   $c = P_{WTGU}R_1^2(X_{l2} + X_m)^2 + P_{WTGU}(X_m^2 - (X_m + X_{l2})(X_m + X_{l1}))^2 - |V|^2R_1(X_m + X_{l2})^2$.
   Then,$R_{eq}$is given by

$$R_{eq} = -max\left|\frac{-b \pm \sqrt{b^2 - 4ac}}{2a}\right| \tag{12}$$

   where a, b, and c are as defined in eq. (11).
3. Knowing R_{eq} compute Q_{WTGU} using eq. (10).

2.2 Variable speed wind turbine generator (VSWG)

Presently, variable speed wind turbine generator is becoming more popular than the fixed speed WTGU because of flexibility in its controller characteristic. The two types of variable speed WTGU are doubly fed induction generator (DFIG) and synchronous generator with front end converter (SGFEC).

When the terminal voltage of the variable speed WTGU is within the normal operating range which is generally specified by the manufacturer ($\pm$ 10 % of the nominal voltage), the active power (P_{WTGU}) output of the WTGU can be obtained directly from the power curve provided by the manufacturer. The reactive power (Q_{WTGU}) output is specified either directly or in terms of power factor (pf). This is because the maximum/minimum current limits of the WTGU are designed so that neither the total current nor any of its components could exceed these limits for any wind speed and terminal voltage within this range.

When the terminal voltage of the variable speed WTGUs is outside the normal range, the current limits of the WTGUs may be violated.

For system performance studies, maintaining the reactive power output of the VS-WTGUs is given first priority. Due to rotor current limits violation, the active power output is reduced so has to maintain the specified reactive power output (i.e., $Q_{WTGU} = Q_{specified}$) of the units. A mathematical model for DFIG in dq reference frame given in [16].

2.2.1 Algorithm for DFIG power output calculation

1. For a given wind speed (u_w), obtain active power (P_{WTGU}) output from the power curve of the WTGU (provided by the manufacturer)
2. If Q is specified, set

$$Q_{WTGU} = Q_{specified} \tag{13}$$

Else, If power factor is specified,

$$Q_{WTGU} = P_{WTGU}\frac{\sqrt{1-\cos\phi^2}}{\cos\phi} \tag{14}$$

3. Check for the terminal voltage (V). If $V < V_{min}$ or $V > V_{max}$
   a. Compute I_{2d}, I_{2q} and I_2 using following equations:

$$I_{2d} = \frac{|V|}{X_m} - \frac{2Q_{WTGU}(X_{l1}+X_m)}{3|V|X_m} \tag{15}$$

$$I_{2q} = -\frac{2P_{WTGU}(X_{l1}+X_m)}{3|V|X_m} \tag{16}$$

$$I_2 = \left|\sqrt{I_{2q}^2 + I_{2d}^2}\right| \tag{17}$$

   b. If I_2 is greater than the maximum current limit (i.e., $I_2 \geq I_{2max}$)
      i. Set $I_2 = I_{2max}$
      ii. For this value of I_2, with I_{2d} unchanged, recalculate I_{2q} as

$$I_{2q} = \left|\sqrt{I_2^2 - I_{2d}^2}\right| \tag{18}$$

      iii. Using this value of I_{2q}, recompute the P_{WTGU}

$$P_{WTGU} = -\frac{3}{2}|V|\frac{X_m}{(X_{l1}+X_m)}I_{2q} \tag{19}$$

2.2.2 Algorithm for SGFEC power output calculation

1. For a given wind speed (u_w), obtain active power (P_{WTGU}) output from the power curve of the WTGU (provided by the manufacturer)
2. If Q is specified, set

$$Q_{WTGU} = Q_{specified} \tag{20}$$

Else, If power factor is specified,

$$Q_{WTGU} = P_{WTGU}\frac{\sqrt{1-\cos\phi^2}}{\cos\phi} \tag{21}$$

3. Check for the terminal voltage (V). If $V < V_{min}$ or $V > V_{max}$
   a. Compute I, I_q and I_d using following equations:

$$I = \left(\frac{S_{WTGU}}{V}\right)^{*} \tag{22}$$

$$I_q = \Re(I) \tag{23}$$

$$I_d = \Im(I) \tag{24}$$

   b. If $|I|$ is greater than the maximum current limit (i.e., $|I| \geq I_{max}$)
      i. Set $|I| = I_{max}$
      ii. For this value of $|I|$, with I_d unchanged, recalculate I_q as

$$I_q = \left|\sqrt{|I|^2 - I_d^2}\right| \tag{25}$$

      iii. Using the value of I_q, recompute the P_{WTGU}

$$P_{WTGU} = |V| I_q \tag{26}$$

3 Models for computing the reactive power output of WTGUs

Based on the mathematical models of various types of WTGUs as discussed in the Section 2 and grid code regulations for reactive power/pf requirements of WTGUs in the system under steady state operating conditions [2, 17, 18], the following models are developed for computing the reactive power output of the WTGUs for system voltage performance studies with WTGUs.

3.1 Fixed/semi-variable speed WTGUs

Asynchronous generators inject active power but consume reactive power. The fixed speed and semi-variable speed WTGUs use induction/asynchronous generator.

The reactive power output of the WTGUs is calculated depending on the type of models used for the analysis.

3.1.1 Voltage dependent model (Volt-depend-model)

The voltage dependent model can be considered in compensated (Volt-depend-comp-model) and uncompensated (Volt-depend-uncomp-model) cases. In both the cases, the actual reactive power demand of the machine is a function of voltage at the terminal bus, and calculated by utilizing the complete equivalent circuit of the conventional induction generator. The advantage of the model is that reactive power can be calculated with a good degree of accuracy on the knowledge of the machine parameters and bus terminal voltage.

In case of voltage dependent compensated model, a reactive compensation devices (either static or dynamic type) is used to improve the pf of the units. The constant pf at the WTGU terminal can be achieved by installing the flexible alternating current transmission system (FACTS) devices, however, it is more expensive. From an economical point of view, a shunt capacitor bank is used at the fixed speed or semi-variable speed WTGU terminals to improve the pf.

For easy implementation, many researchers in the past have assumed the value of the shunt capacitive reactance at the WTGU terminal is same as the magnetizing reactance of the respective units [7].

Because of improved voltage at the terminals due to compensation, this type of model is generally used for the system studies with fixed/semi-variable speed WTGUs [7, 13, 19, 20].

In both the models, the value of the reactive power must be updated at each iterations of the power flow analysis. Hence, the computational effort will be more when this type of model is adapted.

3.1.2 Voltage independent model (Volt-independ-model)

This model is similar to the voltage dependent uncompensated model but it is not iterative. The reactive power demand of the machine is calculated by utilizing the complete equivalent circuit of conventional induction generator with the assumptions that the voltage at the terminal bus is assumed to be nominal value (i.e., V=1.0 p.u.). The advantage of this model is that the reactive power is calculated at the beginning of the iteration and is constant/same till the end of the analysis. There is no need to update its value in each iterations. Therefore, the computational effort will be less as compared to the voltage dependent model.

3.1.3 PX model

A PX model is characterized by an active power injection in parallel with a nodal reactance [8]. This is considered as PQ model with the given value of active power P and Q=0. For power flow analysis, the magnetizing admittance $Y = 1/jX_m$ is included in the nodal admittance matrix. Once power flow is converged, the actual reactive power consumed by the machine can be calculated as $Q = V^2/X_m$.

This model introduces some modifications in the conventional power flow algorithms, thereby, increasing the total number of iterations. The good accuracy in the calculation of the reactive power can be achieved if voltage at the terminal bus is very close to the nominal value ($V = 1.0$ p.u.), but the level of accuracy decreases if the voltage is far away from the nominal value.

3.1.4 Power factor based model (Pf-based-model)

Since a mandate requirement for the plant (WTGUs/wind farms) owners to maintain the pf of their units as per the industry practice or grid code requirements [2, 3, 18], the impact of WTGUs on the system operation is the same irrespective of the models adapted for the calculation of reactive power demand of fixed/semi-variable speed WTGUs. In addition, to overcome the difficulties of other models, power factor based model is proposed, which is in compliance with grid code regulation. For system studies under power factor based model, the reactive power output of the fixed/semi-variable speed WTGUs is calculated by considering the power factor of 0.95 leading (inductive) as per prevailing industry practice.

The advantage of this model is that it does not require more iterations and values are constant till the end of the power flow analysis. Hence, the computational effort will come down when this type of model is adapted for the power flow analysis.

3.2 Variable speed WTGUs

The doubly fed induction generator (DFIG) and synchronous generator with front end converter (SGFEC) are currently the most common wind technologies installed in wind farms. Both configurations are variable speed wind turbines. Because of advancement in power electronics converter design, the VS-WTGUs have the ability to control active and reactive power independently, and meet the grid code requirements. The main advantage of the variable speed WTGUs is the ability to control the reactive power without installing additional capacitive support.

To address the impact of VS-WTGUs on system voltage performance, the variable speed WTGUs are operated in following modes:

1. UPF mode of operation,
2. 0.95 lagging power factor (capacitive) mode of operation, and
3. 0.95 leading power factor (inductive) mode of operation.

4 Power flow analysis of the system with WTGUs

Power flow (PF) analysis is the primary tool for assessing the operation of the system in steady state. For power flow analysis of the system with WTGUs, the wind turbine generators (both fixed/semi-variable speed and variable speed) are usually represented by PQ buses (these units can be considered as load with negative real power injection). However, the variable speed WTGUs can be treated as *PV* buses. Due to commercial and other reasons, this feature may not be implemented at individual WTGUs [21]. But, the voltage control feature may be implemented for the transmission system studies (such as system planning and other studies) with an aggregated model [21–23] of wind farms (which comprises of several variable speed WTGUs) [13].

5 System studies and discussions

5.1 Modified 27-bus equivalent distribution test system

A modified 27-bus equivalent distribution test system, which could be viewed as a typical example of primary distribution system with dispersed generation has been considered for the analysis. A 27-bus, 11 kV distribution test system introduced with five WTGUs at five buses. The single-line diagram of this system is shown in Figure 1.

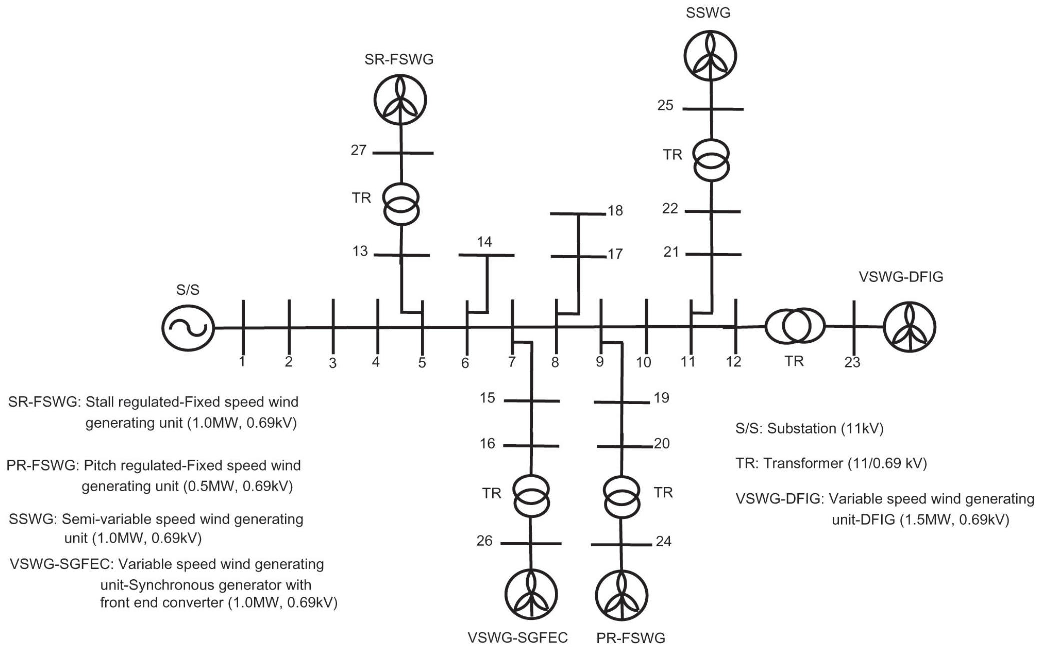

Figure 1 Single-line diagram of modified 27-bus equivalent distribution test system with wind integration.

The system has an initial base-case (peak) load of 8.745 MW and 4.29 MVAr. The system data is taken from [24] and also given in Appendix B for quick reference. The stall regulated fixed speed wind generator (SR-FSWG), pitch regulated fixed speed wind generator (PR-FSWG), semi-variable speed wind generator (SSWG), and variable speed wind generators (VSWGs), both DFIG and SGFEC are connected at different points of the distribution system through five transformers.

The impact of wind power output on distribution system voltage performance has been studied for the following scenarios: Scenario-1: Voltage performance analysis of the system with rated power output of WTGUs for the different PQ models as discussed in the Section 2. Based on these models, a comparative analysis is also carried out to access the impact of wind generation on distribution system voltage performance. Scenario-2: Voltage performance analysis of the system for various power output levels of WTGUs.

The active power output of WTGUs are obtained directly from the power curve provided by the manufacturer. However, the reactive power output of the fixed/semi-variable speed WTGUs is computed depending on the type of PQ models adapted for the studies.

5.1.1 Scenario-1: Voltage performance and comparative analysis of the system with rated power output of WTGUs

Voltage performance and comparative analysis of the system are carried out by considering the different PQ models of fixed/semi-variable speed WTGUs and different fixed pf mode of operation of VS-WTGUs (i.e., either UPF or 0.95 leading/lagging power factor) in the power flow analysis. The power flow solution using Newton-Raphson method incorporating various types of wind generators, has been obtained for all different PQ models of WTGUs as discussed in the Section 3. For all the models, the real and reactive power output as well as the voltage magnitude at the WTGU terminal buses obtained at the end of the power flow solution is summarized in Table 1. This system is again evaluated with various performance indices or parameters, viz., system power loss (P_{loss} and Q_{loss}) and load bus voltage profile parameters (V_{min}, V_{max}, STDEV(V), $\sum (V_d - V_a)^2$ i.e., sum of the square of the voltage deviation from desired voltage of the buses). The system performance parameters for the different PQ models are summarized in Table 2. The system bus voltage magnitude for the different power factor mode of operation of VS-WTGUs for all PQ models of fixed/semi-variable speed wind generators is shown in Figure 2 – Figure 4.

Table 1: WTGUs performance parameters and comparative analysis of modified 27-bus equivalent distribution test system.

VS-WTGU mode→ Bus No.	Input (MW)	UPF P (MW)	UPF Q (MVAr)	UPF Volt. (p.u.)	0.95 lagging pf P (MW)	0.95 lagging pf Q (MVAr)	0.95 lagging pf Volt. (p.u.)	0.95 leading pf P (MW)	0.95 leading pf Q (MVAr)	0.95 leading pf Volt. (p.u.)
Power factor based model (Pf-based-model)										
23	1.5	1.5	0	0.91039	1.5	0.493	0.93931	1.3731	−0.493	0.87722
24	0.5	0.5	−0.1643	0.89881	0.5	−0.1643	0.91038	0.5	−0.1643	0.88496
25	1	1	−0.3287	0.89551	1	−0.3287	0.90894	1	−0.3287	0.87931
26	1	1	0	0.92558	1	0.3287	0.94815	1	−0.3287	0.90054
27	1	1	−0.3287	0.93542	1	−0.3287	0.94186	1	−0.3287	0.92778
Total	5	5	−0.8217	–	5	0	–	4.8731	−1.6434	–
Voltage dependent compensated model (Volt-depend-comp-model)										
23	1.5	1.5	0	0.90893	1.5	0.493	0.9385	1.3681	−0.493	0.87418
24	0.5	0.5	−0.139	0.89957	0.5	−0.1277	0.91259	0.5	−0.1529	0.88323
25	1	1	−0.3786	0.8918	1	−0.3612	0.90669	1	−0.4028	0.87294
26	1	1	0	0.92443	1	0.3287	0.94746	0.9407	−0.3287	0.89775
27	1	0.9619	−0.4084	0.93099	0.9623	−0.3993	0.93814	0.9614	−0.4204	0.922
Total	5	4.9619	−0.926	–	4.9623	−0.0665	–	4.7702	−1.7978	–
Voltage dependent uncompensated model (Volt-depend-uncomp-model)										
23	1.5	1.3323	0	0.89335	1.5	0.493	0.92623	1.3456	−0.493	0.86033
24	0.5	0.5	−0.3778	0.86608	0.5	−0.373	0.88103	0.5	−0.3824	0.85131
25	1	1	−0.6738	0.86293	1	−0.6602	0.88053	1	−0.6905	0.84562
26	1	1	0	0.91382	1	0.3287	0.93855	0.929	−0.3287	0.88774
27	1	0.9607	−0.6822	0.91191	0.9612	−0.6749	0.92019	0.9601	−0.6904	0.90353
Total	5	4.793	−1.7338	–	4.9612	−0.8864	–	4.7347	−2.585	–
Voltage independent model (Volt-independ-model)										
23	1.5	1.3357	0	0.89591	1.5	0.493	0.92816	1.3511	−0.493	0.8637
24	0.5	0.5	−0.3262	0.87287	0.5	−0.3262	0.88681	0.5	−0.3262	0.85924
25	1	1	−0.6227	0.86795	1	−0.6227	0.88427	1	−0.6227	0.85224
26	1	1	0	0.91567	1	0.3287	0.93997	0.9318	−0.3287	0.89016
27	1	0.9823	−0.6457	0.91495	0.9823	−0.6457	0.92261	0.9823	−0.6457	0.90731
Total	5	4.818	−1.5946	–	4.9823	−0.7729	–	4.7652	−2.4163	–
PX model (PX-model)										

23	1.5	1.5	0	0.91273	1.5	0.493	0.9413	1.3777	−0.493	0.88008
24	0.5	0.5	−0.2303	0.90493	0.5	−0.2359	0.91595	0.5	−0.2236	0.8918
25	1	1	−0.2795	0.90004	1	−0.2875	0.91279	1	−0.2701	0.88477
26	1	1	0	0.92732	1	0.3287	0.94966	1	−0.3287	0.90262
27	1	1	−0.2626	0.93936	1	−0.266	0.94549	1	−0.2585	0.93213
Total	5	5	−0.7724	–	5	0.0323	–	4.8777	−1.5739	–

The landscape version of this table is available for download as supplemental material.

Table 2: System-wise performance parameters and comparative analysis of modified 27-bus equivalent distribution test system.

	P_{loss} (MW)	Q_{loss} (MVAr)	V_{min} (p.u.)	V_{max} (p.u.)	SthEV(V) (p.u.)	$\sum(V_d - V_a)^2$ (p.u.)	No. of PF iteration
No-wind	0.8874	1.1169	0.85195	0.98603	0.03766	0.28741	4
VS-WTGUs operating mode: UPF							
Pf-based-model	0.39276	0.6826	0.90349	0.99027	0.02487	0.13142	4
Volt-depend-comp-model	0.40443	0.6984	0.90167	0.9901	0.02519	0.13545	12
Volt-depend-uncomp-model	0.52658	0.8768	0.88448	0.88448	0.02924	0.17819	12
Volt-independ-model	0.50312	0.8404	0.88742	0.98903	0.02855	0.17036	10
PX-model	0.37434	0.6549	0.90604	0.99049	0.02426	0.12518	4
VS-WTGUs operating mode: 0.95 lagging power factor							
Pf-based-model	0.3081	0.5784	0.91678	0.99134	0.02139	0.09993	4
Volt-depend-comp-model	0.31388	0.5856	0.91574	0.99122	0.02153	0.10197	12
Volt-depend-uncomp-model	0.40824	0.7407	0.90111	0.9901	0.02489	0.13334	10
Volt-independ-model	0.39247	0.7155	0.90335	0.99028	0.02436	0.12807	4
PX-model	0.29456	0.5574	0.91856	0.99153	0.02086	0.09519	4
VS-WTGUs operating mode: 0.95 leading power factor							
Pf-based-model	0.51373	0.8441	0.88747	0.98901	0.02911	0.17471	9
Volt-depend-comp-model	0.53907	0.8749	0.88397	0.9887	0.02983	0.18416	14
Volt-depend-uncomp-model	0.6762	1.0847	0.8683	0.98749	0.03348	0.22901	12
Volt-independ-model	0.64193	1.0328	0.8721	0.9878	0.0326	0.2177	10
PX-model	0.48853	0.8075	0.89051	0.98927	0.02836	0.16621	9

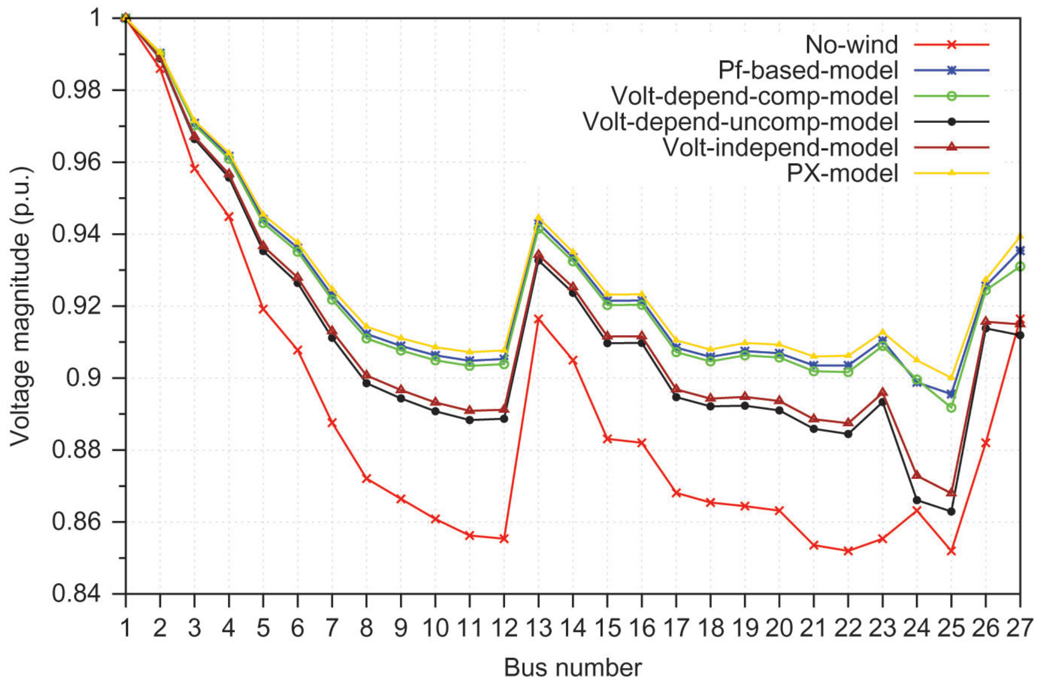

Figure 2 Voltage profile of modified 27-bus equivalent distribution test system: UPF case of VS-WTGUs.

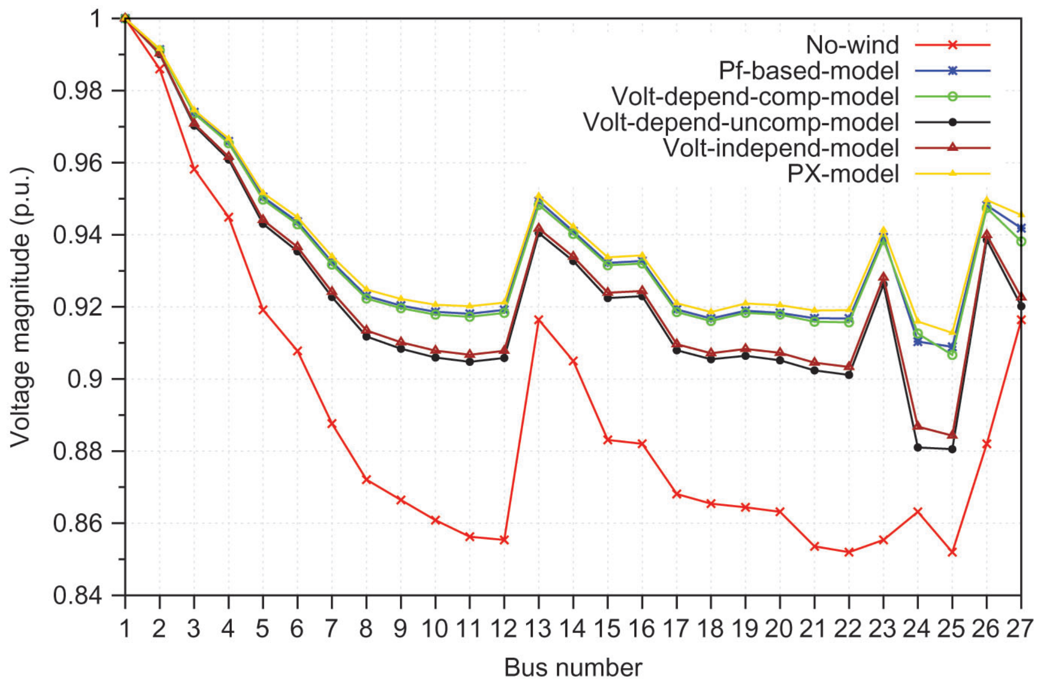

Figure 3 Voltage profile of modified 27-bus equivalent distribution test system: 0.95 lagging pf case of VS-WTGUs.

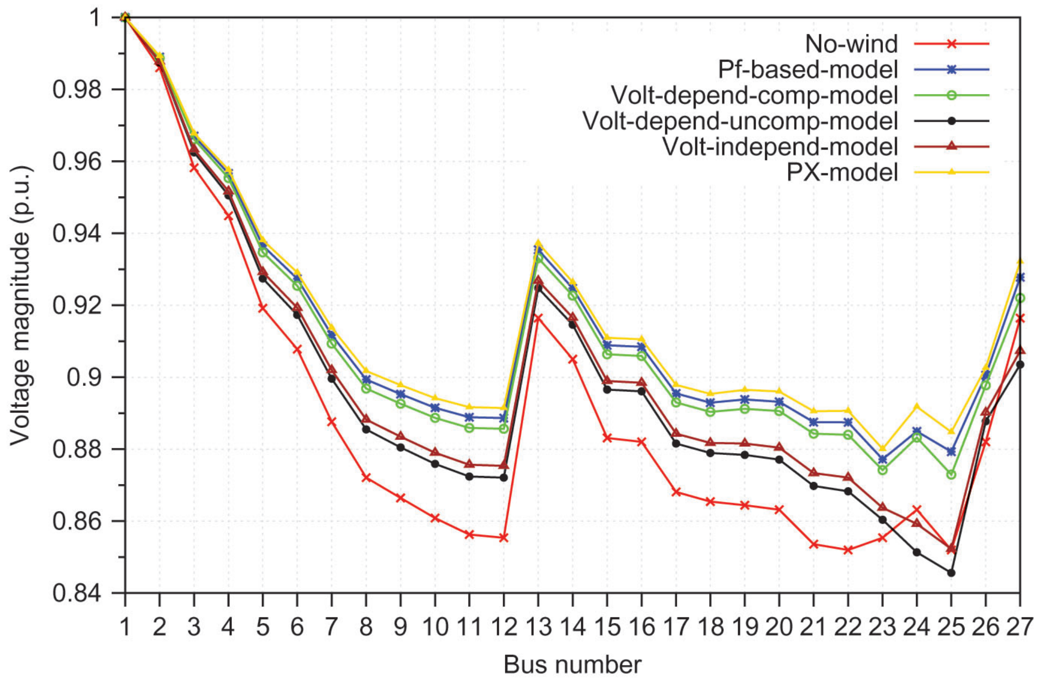

Figure 4 Voltage profile of modified 27-bus equivalent distribution test system: 0.95 leading pf case of VS-WTGUs.

Discussions

It can be observed from the Table 2 and Figures (Figure 2 to Figure 4) that once the real power generation from the WTGUs is made available to the system, the voltage magnitude at all the load buses increases from the base-case (peak load) condition. This increase in voltage at the load buses is due to increase in real power output of the WTGUs in-spite of the increase in reactive power output of wind generators. It can be also seen that when the variable speed wind generators are operated in 0.95 leading power factor (inductive) mode, the voltage magnitude at the load buses are poorer than that operated in either UPF or 0.95 lagging power factor (capacitive) mode. Therefore, the system is more prone to voltage instability in case the variable speed wind generators are to be operated in leading power factor mode during peak load conditions. The improved system voltage performance can be obtained when variable speed wind generators are operated in either UPF or 0.95 lagging power factor mode.

In this study, the variable speed WTGUs are operated in a such way that it should maintain the specified reactive power (Q_{WTGU}) output irrespective of the terminal voltage at the buses. During low voltage operating condition (may be in case of leading power factor (inductive) mode of VS-WTGUs operation), the active power (P_{WTGU}) output of the variable speed wind generators (DFIG/SGFEC) are reduced so as to maintain the specified reactive power (Q_{WTGU}) output at the WTGU terminals due to rotor current limit violation of the machine. This phenomenon is clearly observed from the Table 1. It is also noticed from the Table that in case of SR-FSWG, the terminal voltage variation has little impact on the active power (P_{WTGU}) output of the machine.

From the system simulation studies, it can be observed that among all the models of fixed/semi-variable speed WTGU, voltage dependent uncompensated model is capturing the actual behaviour of the induction machine in system operation. Because the reactive power output of the fixed/semi-variable speed WTGUs is obtained from complete equivalent circuit parameters of the induction machine and voltage at the terminal buses. The reactive power consumption of the fixed/semi-variable speed WTGUs is increases with the decrease in terminal voltage. Therefore, the reactive power drawn from the grid is higher at lower voltages. For system operation with fixed/semi-variable speed WTGUs, the voltage dependent uncompensated model is generally not preferred due to poor power factor operation of the machine (which may lead to poor voltage profile in the system). Moreover, it is not meeting the grid code requirements imposed by the system operators. On the other hand, the system voltage profile produced by the voltage dependent compensated model is much better as compared with that from voltage dependent uncompensated model because of compensation. However, in both the models the value of reactive power must be updated at each iteration of the power flow analysis, and computational efforts required is almost the same as it can be observed from the number of iterations are taken to get the converged solutions (refer Table 2).

Similar to that the voltage independent model is also based on the complete equivalent circuit representation of the induction generator. This model is computationally more efficient as compared with voltage dependent models. It takes less iterations to get the converged solutions. This is because the reactive power consumption of the machine is not affected by the voltage variation during the operation. The reactive power consumption of the machine is calculated at the nominal voltage (V=1.0 p.u.) value and its value remains the same till the end of the solutions. However, still the system voltage profile produced by this model is in close agreement with that produced by the voltage dependent uncompensated model.

On the contrary, the system voltage profile produced by the power factor based model is better as compared with voltage dependent uncompensated and voltage independent models. Moreover, the system performance produced by the voltage dependent compensated model is closely in agreement with that produced by the power factor based model as it clearly observed from Figure 2 to Figure 4. It can also be seen from the Table 2 that power factor based model is computationally more efficient as compared with other three models (which are based on voltage) as it takes less number of iterations to get the converged solution.

In case of PX model, the reactive power consumed by the WTGUs is the function of the voltage, which depends on the system operating condition. When system under low voltage condition, the reactive power demand of the WTGUs is significantly less. Therefore, the actual effect of induction generator may not get reflected in the system operation. Because of low voltage at the terminal, the pf of the WTGU terminals almost nearer/close to UPF. Hence, system performance is better as compared to other models. However, this model can produce the performance somewhat close to the voltage independent model when the terminal voltage is at the nominal value i.e., V=1.0 p.u. Hence, the system performance produced by the PX model is not consistent as it depends on the voltage at the terminal bus and value of the magnetizing reactance of the respective units.

Inference

From these discussions, it can be inferred that the power factor based method can be used as a substitute model for the voltage dependent compensated model (it is being used more frequently in system analysis with fixed/semi-variable speed WTGUs) due to the implementation of grid code requirements by the system operators [2, 3, 18]. It requires less computational efforts and at the same time producing the system performance is in close agreement with that from voltage dependent compensated model. Therefore, the main requirement for the power factor based model is that the value of the power factor of fixed/semi-variable speed WTGUs are to be chosen as per the grid code regulation.

5.1.2 Scenario-2: Voltage performance analysis of the system for various power output levels of WTGUs

Similar to Scenario-1, the case studies have been carried out for the system with various power output levels of WTGUs (both fixed/semi-variable speed and variable speed WTGUs) considering the power factor based model for the fixed/semi-variable speed WTGUs, and fixed different power factor mode of operation for the VS-WTGUs (i.e., either UPF or 0.95 leading/lagging power factor).

The power flow solution for the various power output levels of WTGUs is obtained. The real and reactive power output as well as the voltage magnitude at the WTGU terminal buses obtained at the end of the power flow solution is summarized in Table 3. The system performance parameters for various power levels of wind generation are summarized in Table 4. The system bus voltage profile for the different power factor mode of operation of VS-WTGUs for various power output levels of WTGUs is shown in Figure 5 – Figure 7. It can be observed from the Table 4 and Figure 5 to Figure 7 that as power level of wind generators is increasing, the system performance is also improving.

It can be also observed from the Table 4 that during leading power factor (inductive) mode of operation of VS-WTGUs, the number of iterations are taken to get the converged solution for 100 % power output of WTGUs is 9 (iterations) and that for 80 % power output is 4 (iterations). This is due to the fact that during the power flow iterations the active power output of the VS-WTGUs are get changed due to rotor current limit violation because of low voltage at the terminals as in case of 100 % power output of wind generators. Hence, it takes more iterations to get the converged solution. However, the active power output of the VS-WTGUs are not changed during the iterations as in case of 80 % power output of the units because the rotor current of the units are well within the minimum and maximum limits.

Table 3: Modified 27-bus equivalent distribution test system for various wind power output levels.

VS-WTGU mode→			UPF			0.95 lagging pf			0.95 leading pf		
	Bus No.		P	Q	Volt.	P	Q	Volt.	P	Q	Volt.
output		Input (MW)	(MW)	(MVAr)	(p.u.)	(MW)	(MVAr)	(p.u.)	(MW)	(MVAr)	(p.u.)

Case-2 (80 %)	23	1.2	1.2	0	0.90121	1.2	0.3944	0.92463	1.2	−0.3944	0.8764
	24	0.4	0.4	−0.1315	0.89321	0.4	−0.1315	0.90251	0.4	−0.1315	0.88329
	25	0.8	0.8	−0.2629	0.88852	0.8	−0.2629	0.89935	0.8	−0.2629	0.877
	26	0.8	0.8	0	0.91826	0.8	0.2629	0.9365	0.8	−0.2629	0.89908
	27	0.8	0.8	−0.2629	0.93264	0.8	−0.2629	0.9378	0.8	−0.2629	0.92714
	Total	4	4	−0.6573	–	4	0	–	4	−1.3146	–
Case-3 (60 %)	23	0.9	0.9	0	0.89119	0.9	0.2958	0.90901	0.9	−0.2958	0.87257
	24	0.3	0.3	−0.0986	0.8869	0.3	−0.0986	0.89394	0.3	−0.0986	0.87951
	25	0.6	0.6	−0.1972	0.88075	0.6	−0.1972	0.88895	0.6	−0.1972	0.87215
	26	0.6	0.6	0	0.91031	0.6	0.1972	0.92415	0.6	−0.1972	0.89593
	27	0.6	0.6	−0.1972	0.92938	0.6	−0.1972	0.93327	0.6	−0.1972	0.9253
	Total	3	3	−0.493	–	3	0	–	3	−0.986	–
Case-4 (40 %)	23	0.6	0.6	0	0.88027	0.6	0.1972	0.89236	0.6	−0.1972	0.86782
	24	0.2	0.2	−0.0657	0.87983	0.2	−0.0657	0.88458	0.2	−0.0657	0.87492
	25	0.4	0.4	−0.1315	0.87211	0.4	−0.1315	0.87766	0.4	−0.1315	0.86639
	26	0.4	0.4	0	0.90167	0.4	0.1315	0.91102	0.4	−0.1315	0.89206
	27	0.4	0.4	−0.1315	0.92562	0.4	−0.1315	0.92824	0.4	−0.1315	0.92292
	Total	2	2	−0.3287	–	2	0	–	2	−0.6574	–
Case-5 (20 %)	23	0.3	0.3	0	0.86836	0.3	0.0986	0.87453	0.3	−0.0986	0.8621
	24	0.1	0.1	-0.0329	0.87193	0.1	−0.0329	0.87435	0.1	−0.0329	0.86948
	25	0.2	0.2	−0.0657	0.86255	0.2	−0.0657	0.86537	0.2	−0.0657	0.85968
	26	0.2	0.2	0	0.89227	0.2	0.0657	0.89703	0.2	−0.0657	0.88745
	27	0.2	0.2	−0.0657	0.92132	0.2	−0.0657	0.92265	0.2	−0.0657	0.91997
	Total	1	1	−0.1643	–	1	0	–	1	−0.3286	–

The landscape version of this table is available for download as supplemental material.

Table 4: System performance parameters of modified 27-bus equivalent distribution test system for various wind power output levels.

Wind power output	P_{loss} (MW)	Q_{loss} (MVAr)	V_{min} (p.u.)	V_{max} (p.u.)	STDEV(V) (p.u.)	$\sum (V_d - V_a)^2$ (p.u.)	No. of PF iteration
No-wind	0.8874	1.1169	0.85195	0.98603	0.03766	0.28741	4
VS-WTGUs operating mode: UPF							
Case-1 (100 %)	0.39276	0.6826	0.90349	0.99027	0.02487	0.13142	4
Case-2 (80 %)	0.42922	0.6625	0.89484	0.98959	0.02702	0.15325	4
Case-3 (60 %)	0.49479	0.6927	0.88543	0.98883	0.02936	0.17899	4
Case-4(40 %)	0.59134	0.7759	0.8752	0.98798	0.0319	0.20933	4
Case-5 (20 %)	0.72122	0.9158	0.86407	0.98705	0.03466	0.24512	4
VS-WTGUs operating mode: 0.95 lagging power factor							
Case-1 (100 %)	0.3081	0.5784	0.91678	0.99134	0.02139	0.09993	4
Case-2 (80 %)	0.36161	0.5799	0.90557	0.99044	0.024192	0.125348	4
Case-3 (60 %)	0.44339	0.63	0.89358	0.98947	0.0272	0.15578	4
Case-4(40 %)	0.55601	0.7326	0.88072	0.98841	0.03043	0.19214	4
Case-5 (20 %)	0.70266	0.8928	0.86689	0.98727	0.03391	0.23554	4
VS-WTGUs operating mode: 0.95 leading power factor							

Case-1 (100 %)	0.51373	0.8441	0.88747	0.98901	0.02911	0.17471	9
Case-2 (80 %)	0.51639	0.784	0.88341	0.98868	0.03005	0.18604	4
Case-3 (60 %)	0.55732	0.7774	0.87688	0.98815	0.03163	0.20507	4
Case-4(40 %)	0.63173	0.8292	0.86949	0.98754	0.03342	0.22787	4
Case-5 (20 %)	0.74109	0.9413	0.86121	0.98683	0.03542	0.25506	4

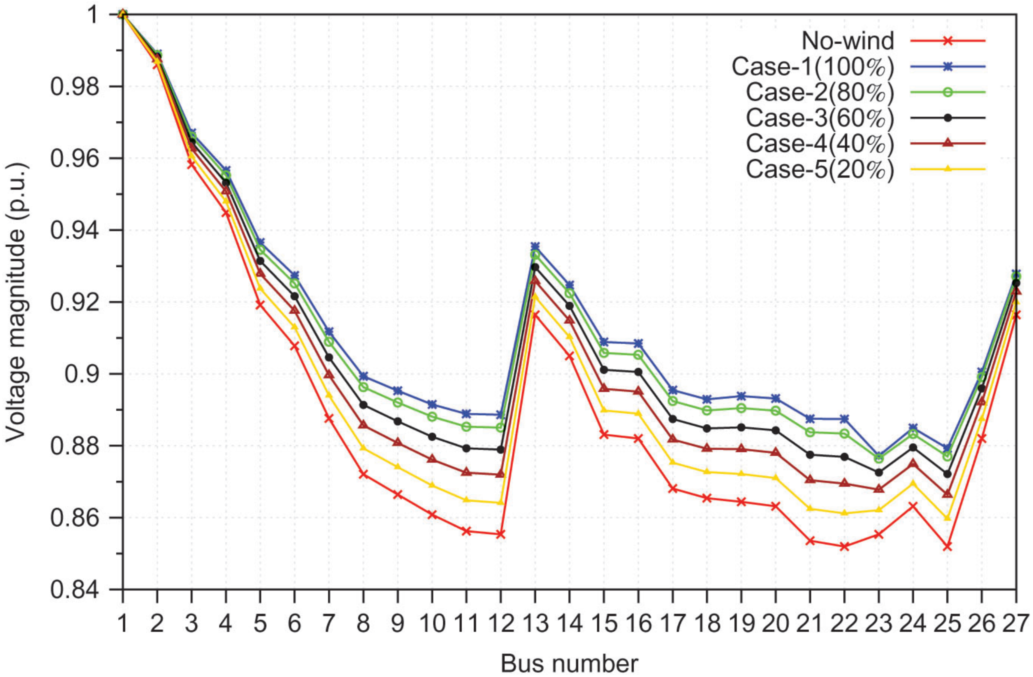

Figure 5 Voltage profile of modified 27-bus equivalent distribution test system for various power levels of WTGUs (leading power factor case of VS-WTGUs).

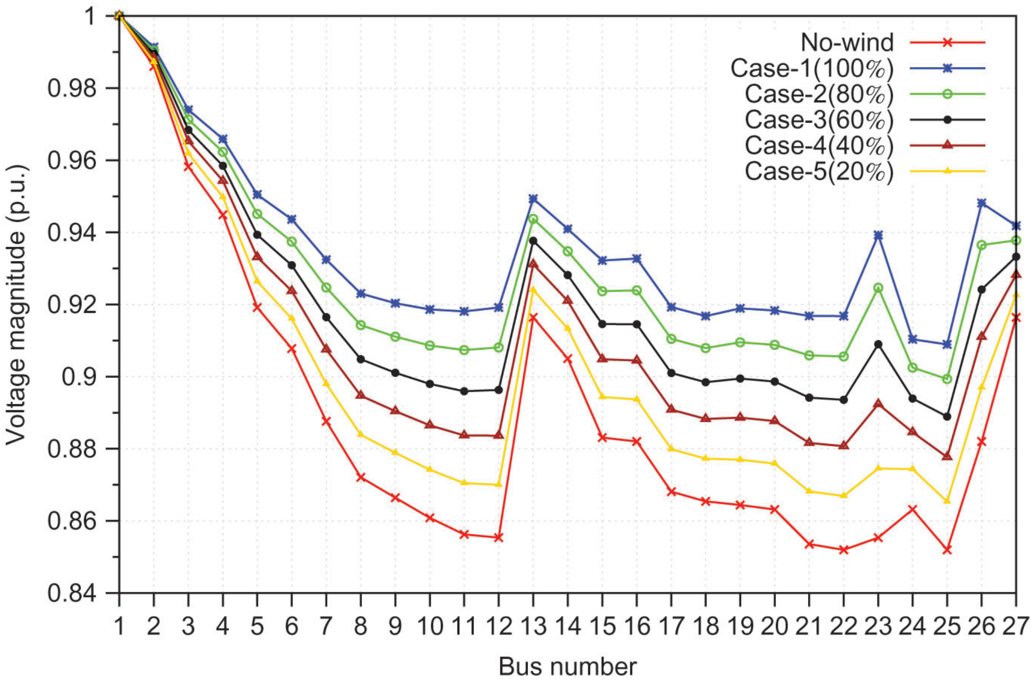

Figure 6 Voltage profile of modified 27-bus equivalent distribution test system for various power levels of WTGUs (lagging power factor case of VS-WTGUs).

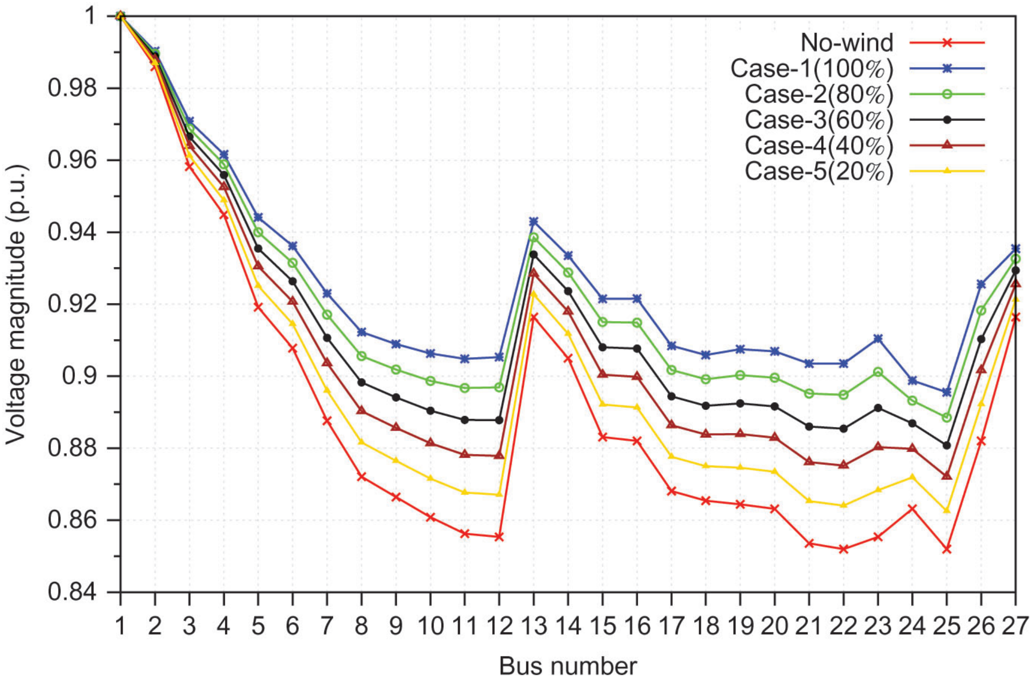

Figure 7 Voltage profile of modified 27-bus equivalent distribution test system for various power levels of WTGUs (UPF case of VS-WTGUs).

6 Conclusion

The voltage performance analysis of the system with various types of WTGUs has been presented. The detailed voltage performance and comparative analysis are carried out by considering the different PQ models used for computing the reactive power output of the WTGUs. The studies are carried out on a modified 27-bus equivalent distribution test system with dispersed wind generation to assess the impact of wind power on the overall system performances. Simulation results show that the improved system voltage performance can be obtained when variable speed wind generators are operated in either UPF or lagging power factor (capacitive) mode. The system may lead to voltage instability in case the variable speed WTGUs are to be operated in leading power factor (inductive) mode during peak load condition. In addition, among all the models of fixed/semi-variable speed WTGUs, the voltage dependent compensated and power factor based models are able to meet the grid code interconnection standards set by the operators in the system. However, in terms of implementation and computational efforts in other models, the power factor based model can be the best choice over the voltage dependent compensated model and other models for the system studies with fixed/semi-variable speed WTGUs.

Appendix

A Mathematical modeling of an induction generator

From the equivalent circuit shown in Figure 8, the expression for the stator current (I_1), magnetizing current (I_m), rotor current (I_2), air gap power (P_g) and the active power (Pe_{IG}) output as well as the reactive power (Qe_{IG}) output are obtained as [25]:

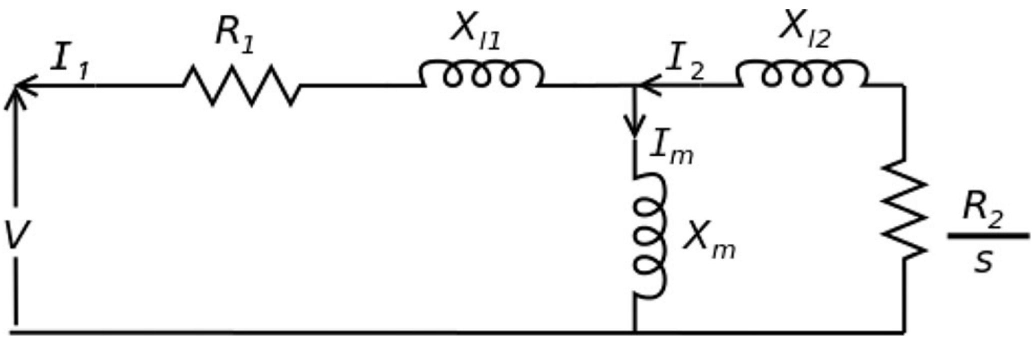

Figure 8 Induction machine equivalent circuit.

$$I_m = \frac{V + I_1(R_1 + jX_{l1})}{jX_m} \tag{27}$$

$$I_1 = \frac{V(\frac{R_2}{s} + jX_{l2} + jX_m)}{[(\frac{R_2}{s} + jX_{l2})(jX_m) + (\frac{R_2}{s} + jX_{l2} + jX_m)(R_1 + jX_{l1})]} \tag{28}$$

$$I_2 = I_1 + I_m \tag{29}$$

$$P_g(V, \omega_r) = -|I_2|^2 R_2 \frac{1-s}{s} \tag{30}$$

$$Pe_{IG} = \Re(VI_1^*) \tag{31}$$

$$Qe_{IG} = \Im(VI_1^*) \tag{32}$$

where, R_1, R_2 are the stator and rotor resistances; X_{l1}, X_{l2}, X_m are the stator leakage reactance, rotor leakage reactance and the magnetizing reactance, respectively; $s = (\omega_s - \omega_r(N/2))/\omega_s$ is the slip; ω_s is the synchronous speed in electrical rad/sec and ω_r is the induction generator rotor speed in mechanical rad/sec; N is the number of poles; V is the voltage at the terminal buses; Pe_{IG} and Qe_{IG} are the active and reactive power output of induction generator.

The equations for Pe_{IG} and Qe_{IG} in terms of the induction generator circuit parameters turn out to be:

$$Pe_{IG} = \frac{[R_1(R_2^2 + s^2(X_m + X_{l2})^2) + sR_2X_m^2]|V|^2}{[R_2R_1 + s(X_m^2 - (X_m + X_{l2})(X_m + X_{l1}))]^2 + [R_2(X_m + X_{l1}) + sR_1(X_m + X_{l2})]^2} \tag{33}$$

$$Qe_{IG} = \frac{[X_mX_{l2}s^2(X_m + X_{l2}) + X_{l1}s^2(X_m + X_{l2})^2 + R_2^2(X_m + X_{l1})]|V|^2}{[R_2R_1 + s(X_m^2 - (X_m + X_{l2})(X_m + X_{l1}))]^2 + [R_2(X_m + X_{l1}) + sR_1(X_m + X_{l2})]^2} \tag{34}$$

B System data of modified 27-bus equivalent distribution test system with wind integration

Table 5: Line data.

From Bus	To Bus	R (p.u.)	X (p.u.)	From Bus	To Bus	R (p.u.)	X (p.u.)
1	2	0.0851	0.1071	5	13	0.2808	0.3534

2	3	0.1702	0.2142	6	14	0.2808	0.3534
3	4	0.0851	0.1071	7	15	0.2808	0.3534
4	5	0.1702	0.2142	15	16	0.1021	0.1285
5	6	0.0851	0.1071	8	17	0.2127	0.2677
6	7	0.1702	0.2142	17	18	0.2553	0.3213
7	8	0.1702	0.2142	9	19	0.1702	0.2142
8	9	0.0851	0.1071	19	20	0.2042	0.257
9	10	0.1276	0.1606	11	21	0.2127	0.2677
10	11	0.1362	0.1714	21	22	0.2553	0.3213
11	12	0.0851	0.1071				

Table 6: Transformer data.

From Bus	To Bus	R (p.u.)	X (p.u.)
12	23	0.3833	2.875
13	27	0.438095	3.2857
16	26	0.438095	3.2857
20	24	0.8889	6.6667
22	25	0.438095	3.2857

Table 7: WTGUs circuit parameters.

WTGUs Type/ Bus No.	R_1 (p.u)	R_2 (p.u)	X_1 (p.u)	X_2 (p.u)	X_m (p.u)	P_{rated} (MW)	V_{rated} (kV)
PR-FSWG (Bus-24)	0.005986	0.0169	0.08212	0.107225	3.5561	0.5	0.69
SSWG (Bus-25)	0.005671	0.00462	0.1525	0.096618	2.8985	1.00	0.69
SR-FSWG (Bus-27)	0.007141	0.0063	0.21552	0.088216	3.3606	1.00	0.69
DFIG (Bus-23)	0.02087	0.014518	0.16198	0.144012	2.610004	1.5	0.69

Table 8: Variable speed wind turbine generators Q limits.

VSWGs Type/ Bus No.	P_{rated} (MW)	Q_{max} (MVAr)	Q_{min} (MVAr)
SGFEC (Bus-26)	1.00	0.3287	-0.3287
DFIG (Bus-23)	1.5	0.493	-0.493

Table 9: Load data.

Bus No.	P (MW)	Q (MVAr)	Bus No.	P (MW)	Q (MVAr)
3	0.375	0.18	13	0.555	0.27
4	0.3	0.15	14	0.555	0.27
5	0.375	0.18	15	0.33	0.165
6	0.3	0.15	16	0.555	0.27
7	0.555	0.27	17	0.45	0.225
8	0.33	0.165	18	0.555	0.27
9	0.555	0.27	19	0.3	0.15
10	0.555	0.27	20	0.33	0.165
11	0.555	0.27	21	0.33	0.165
12	0.555	0.27	22	0.33	0.165

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Table 1: WTGUs performance parameters and comparative analysis of modified 27-bus equivalent distribution test system

VS-WTGUs operating mode →		UPF			0.95 lagging power factor			0.95 leading power factor		
Bus No. (WTGU Type)	Specified input(MW)	P_{WTGU} (MW)	Q_{WTGU} (MVAr)	WTGU Volt.(p.u.)	P_{WTGU} (MW)	Q_{WTGU} (MVAr)	WTGU Volt.(p.u.)	P_{WTGU} (MW)	Q_{WTGU} (MVAr)	WTGU Volt.(p.u.)
Power factor based model (Pf-based-model)										
23 (VSWG-DFIG)	1.5	1.5	0	0.91039	1.5	0.493	0.93931	1.3731	-0.493	0.87722
24 (PR-FSWG)	0.5	0.5	-0.1643	0.89881	0.5	-0.1643	0.91038	0.5	-0.1643	0.88496
25 (SSWG)	1	1	-0.3287	0.89551	1	-0.3287	0.90894	1	-0.3287	0.87931
26 (VSWG-SGFEC)	1	1	0	0.92558	1	0.3287	0.94815	1	-0.3287	0.90054
27 (SR-FSWG)	1	1	-0.3287	0.93542	1	-0.3287	0.94186	1	-0.3287	0.92778
Total	5	5	-0.8217	–	5	0	–	4.8731	-1.6434	–
Voltage dependent compensated model (Volt-depend-comp-model)										
23 (VSWG-DFIG)	1.5	1.5	0	0.90893	1.5	0.493	0.9385	1.3681	-0.493	0.87418
24 (PR-FSWG)	0.5	0.5	-0.139	0.89957	0.5	-0.1277	0.91259	0.5	-0.1529	0.88323
25 (SSWG)	1	1	-0.3786	0.8918	1	-0.3612	0.90669	1	-0.4028	0.87294
26 (VSWG-SGFEC)	1	1	0	0.92443	1	0.3287	0.94746	0.9407	-0.3287	0.89775
27 (SR-FSWG)	1	0.9619	-0.4084	0.93099	0.9623	-0.3993	0.93814	0.9614	-0.4204	0.922
Total	5	4.9619	-0.926	–	4.9623	-0.0665	–	4.7702	-1.7978	–
Voltage dependent uncompensated model (Volt-depend-uncomp-model)										
23 (VSWG-DFIG)	1.5	1.3323	0	0.89335	1.5	0.493	0.92623	1.3456	-0.493	0.86033
24 (PR-FSWG)	0.5	0.5	-0.3778	0.86608	0.5	-0.373	0.88103	0.5	-0.3824	0.85131
25 (SSWG)	1	1	-0.6738	0.86293	1	-0.6602	0.88053	1	-0.6905	0.84562
26 (VSWG-SGFEC)	1	1	0	0.91382	1	0.3287	0.93855	0.929	-0.3287	0.88774
27 (SR-FSWG)	1	0.9607	-0.6822	0.91191	0.9612	-0.6749	0.92019	0.9601	-0.6904	0.90353
Total	5	4.793	-1.7338	–	4.9612	-0.8864	–	4.7347	-2.585	–
Voltage independent model (Volt-independ-model)										
23 (VSWG-DFIG)	1.5	1.3357	0	0.89591	1.5	0.493	0.92816	1.3511	-0.493	0.8637
24 (PR-FSWG)	0.5	0.5	-0.3262	0.87287	0.5	-0.3262	0.88681	0.5	-0.3262	0.85924
25 (SSWG)	1	1	-0.6227	0.86795	1	-0.6227	0.88427	1	-0.6227	0.85224
26 (VSWG-SGFEC)	1	1	0	0.91567	1	0.3287	0.93997	0.9318	-0.3287	0.89016
27 (SR-FSWG)	1	0.9823	-0.6457	0.91495	0.9823	-0.6457	0.92261	0.9823	-0.6457	0.90731
Total	5	4.818	-1.5946	–	4.9823	-0.7729	–	4.7652	-2.4163	–
PX model (PX-model)										
23 (VSWG-DFIG)	1.5	1.5	0	0.91273	1.5	0.493	0.9413	1.3777	-0.493	0.88008
24 (PR-FSWG)	0.5	0.5	-0.2303	0.90493	0.5	-0.2359	0.91595	0.5	-0.2236	0.8918
25 (SSWG)	1	1	-0.2795	0.90004	1	-0.2875	0.91279	1	-0.2701	0.88477
26 (VSWG-SGFEC)	1	1	0	0.92732	1	0.3287	0.94966	1	-0.3287	0.90262
27 (SR-FSWG)	1	1	-0.2626	0.93936	1	-0.266	0.94549	1	-0.2585	0.93213
Total	5	5	-0.7724	–	5	0.0323	–	4.8777	-1.5739	–

Table 2: System-wise performance parameters and comparative analysis of modified 27-bus equivalent distribution test system

	P_{loss} (MW)	Q_{loss} (MVAr)	V_{min} (p.u.)	V_{max} (p.u.)	STDEV(V) (p.u.)	$\sum(V_d - V_a)^2$ (p.u.)	No. of PF iteration
No-wind	0.8874	1.1169	0.85195	0.98603	0.03766	0.28741	4
VS-WTGUs operating mode: UPF							
Pf-based-model	0.39276	0.6826	0.90349	0.99027	0.02487	0.13142	4
Volt-depend-comp-model	0.40443	0.6984	0.90167	0.9901	0.02519	0.13545	12
Volt-depend-uncomp-model	0.52658	0.8768	0.88448	0.88448	0.02924	0.17819	12
Volt-independ-model	0.50312	0.8404	0.88742	0.98903	0.02855	0.17036	10
PX-model	0.37434	0.6549	0.90604	0.99049	0.02426	0.12518	4
VS-WTGUs operating mode: 0.95 lagging power factor							
Pf-based-model	0.3081	0.5784	0.91678	0.99134	0.02139	0.09993	4
Volt-depend-comp-model	0.31388	0.5856	0.91574	0.99122	0.02153	0.10197	12
Volt-depend-uncomp-model	0.40824	0.7407	0.90111	0.9901	0.02489	0.13334	10
Volt-independ-model	0.39247	0.7155	0.90335	0.99028	0.02436	0.12807	4
PX-model	0.29456	0.5574	0.91856	0.99153	0.02086	0.09519	4
VS-WTGUs operating mode: 0.95 leading power factor							
Pf-based-model	0.51373	0.8441	0.88747	0.98901	0.02911	0.17471	9
Volt-depend-comp-model	0.53907	0.8749	0.88397	0.9887	0.02983	0.18416	14
Volt-depend-uncomp-model	0.6762	1.0847	0.8683	0.98749	0.03348	0.22901	12
Volt-independ-model	0.64193	1.0328	0.8721	0.9878	0.0326	0.2177	10
PX-model	0.48853	0.8075	0.89051	0.98927	0.02836	0.16621	9

Table 3: Modified 27-bus equivalent distribution test system for various wind power output levels

VS-WTGUs operating mode →			UPF			0.95 lagging power factor			0.95 leading power factor		
Wind power output levels	Bus No. (WTGU Type)	Specified input(MW)	P_{WTGU} (MW)	Q_{WTGU} (MVAr)	WTGU Volt.(p.u.)	P_{WTGU} (MW)	Q_{WTGU} (MVAr)	WTGU Volt.(p.u.)	P_{WTGU} (MW)	Q_{WTGU} (MVAr)	WTGU Volt.(p.u.)
Case-2 (80%)	23 (VSWG-DFIG)	1.2	1.2	0	0.90121	1.2	0.3944	0.92463	1.2	-0.3944	0.8764
	24 (PR-FSWG)	0.4	0.4	-0.1315	0.89321	0.4	-0.1315	0.90251	0.4	-0.1315	0.88329
	25 (SSWG)	0.8	0.8	-0.2629	0.88852	0.8	-0.2629	0.89935	0.8	-0.2629	0.877
	26 (VSWG-SGFEC)	0.8	0.8	0	0.91826	0.8	0.2629	0.9365	0.8	-0.2629	0.89908
	27 (SR-FSWG)	0.8	0.8	-0.2629	0.93264	0.8	-0.2629	0.9378	0.8	-0.2629	0.92714
	Total	4	4	-0.6573	–	4	0	–	4	-1.3146	–
Case-3 (60%)	23 (VSWG-DFIG)	0.9	0.9	0	0.89119	0.9	0.2958	0.90901	0.9	-0.2958	0.87257
	24 (PR-FSWG)	0.3	0.3	-0.0986	0.8869	0.3	-0.0986	0.89394	0.3	-0.0986	0.87951
	25 (SSWG)	0.6	0.6	-0.1972	0.88075	0.6	-0.1972	0.88895	0.6	-0.1972	0.87215
	26 (VSWG-SGFEC)	0.6	0.6	0	0.91031	0.6	0.1972	0.92415	0.6	-0.1972	0.89593
	27 (SR-FSWG)	0.6	0.6	-0.1972	0.92938	0.6	-0.1972	0.93327	0.6	-0.1972	0.9253
	Total	3	3	-0.493	–	3	0	–	3	-0.986	–
Case-4 (40%)	23 (VSWG-DFIG)	0.6	0.6	0	0.88027	0.6	0.1972	0.89236	0.6	-0.1972	0.86782
	24 (PR-FSWG)	0.2	0.2	-0.0657	0.87983	0.2	-0.0657	0.88458	0.2	-0.0657	0.87492
	25 (SSWG)	0.4	0.4	-0.1315	0.87211	0.4	-0.1315	0.87766	0.4	-0.1315	0.86639
	26 (VSWG-SGFEC)	0.4	0.4	0	0.90167	0.4	0.1315	0.91102	0.4	-0.1315	0.89206
	27 (SR-FSWG)	0.4	0.4	-0.1315	0.92562	0.4	-0.1315	0.92824	0.4	-0.1315	0.92292
	Total	2	2	-0.3287	–	2	0	–	2	-0.6574	–
Case-5 (20%)	23 (VSWG-DFIG)	0.3	0.3	0	0.86836	0.3	0.0986	0.87453	0.3	-0.0986	0.8621
	24 (PR-FSWG)	0.1	0.1	-0.0329	0.87193	0.1	-0.0329	0.87435	0.1	-0.0329	0.86948
	25 (SSWG)	0.2	0.2	-0.0657	0.86255	0.2	-0.0657	0.86537	0.2	-0.0657	0.85968
	26 (VSWG-SGFEC)	0.2	0.2	0	0.89227	0.2	0.0657	0.89703	0.2	-0.0657	0.88745
	27 (SR-FSWG)	0.2	0.2	-0.0657	0.92132	0.2	-0.0657	0.92265	0.2	-0.0657	0.91997
	Total	1	1	-0.1643	–	1	0	–	1	-0.3286	–

Table 4: System performance parameters of modified 27-bus equivalent distribution test system for various wind power output levels

Wind power output	P_{loss} (MW)	Q_{loss} (MVAr)	V_{min} (p.u.)	V_{max} (p.u.)	STDEV(V) (p.u.)	$\sum(V_d - V_a)^2$ (p.u.)	No. of PF iteration
No-wind	0.8874	1.1169	0.85195	0.98603	0.03766	0.28741	4
VS-WTGUs operating mode: UPF							
Case-1 (100%)	0.39276	0.6826	0.90349	0.99027	0.02487	0.13142	4
Case-2 (80%)	0.42922	0.6625	0.89484	0.98959	0.02702	0.15325	4
Case-3 (60%)	0.49479	0.6927	0.88543	0.98883	0.02936	0.17899	4
Case-4(40%)	0.59134	0.7759	0.8752	0.98798	0.0319	0.20933	4
Case-5 (20%)	0.72122	0.9158	0.86407	0.98705	0.03466	0.24512	4
VS-WTGUs operating mode: 0.95 lagging power factor							
Case-1 (100%)	0.3081	0.5784	0.91678	0.99134	0.02139	0.09993	4
Case-2 (80%)	0.36161	0.5799	0.90557	0.99044	0.024192	0.125348	4
Case-3 (60%)	0.44339	0.63	0.89358	0.98947	0.0272	0.15578	4
Case-4(40%)	0.55601	0.7326	0.88072	0.98841	0.03043	0.19214	4
Case-5 (20%)	0.70266	0.8928	0.86689	0.98727	0.03391	0.23554	4
VS-WTGUs operating mode: 0.95 leading power factor							
Case-1 (100%)	0.51373	0.8441	0.88747	0.98901	0.02911	0.17471	9
Case-2 (80%)	0.51639	0.784	0.88341	0.98868	0.03005	0.18604	4
Case-3 (60%)	0.55732	0.7774	0.87688	0.98815	0.03163	0.20507	4
Case-4(40%)	0.63173	0.8292	0.86949	0.98754	0.03342	0.22787	4
Case-5 (20%)	0.74109	0.9413	0.86121	0.98683	0.03542	0.25506	4