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Electric Power Systems Research 76 (2006) 844–856
ELECTRIC POWER SYSTEMS RESEARCH
www.elsevier.com/locate/epsr

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

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Received 28 December 2004; received in revised form 22 September 2005; accepted 15 October 2005
Available online 28 December 2005

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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doi:10.1016/j.epsr.2005.10.012

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