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Evaluation of power flow solutions with fixed speed wind turbine generating systems

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ABSTRACT

An increased penetration of wind turbine generating systems into power grid calls for proper modeling of the systems and incorporating the model into various computational tools used in power system operation and planning studies. This paper proposes a simple method of incorporating the exact equivalent circuit of a fixed speed wind generator into conventional power flow program. The method simply adds two internal buses of the generator to include all parameters of the equivalent circuit. For a given wind speed, the active power injection into one of the internal buses is determined through wind turbine power curve supplied by the manufacturers. The internal buses of the model can be treated as a traditional *P–Q* bus and thus can easily be incorporated into any standard power flow program by simply augmenting the input data files and without modifying source codes of the program. The effectiveness of the proposed method is then evaluated on a simple system as well as on the IEEE 30- and 118-bus systems. The results of the simple system are also compared with those found through Matlab/Simulink using dynamic model of wind generating system given in SimPowerSystems blockset.

1. Introduction

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

A WTGS can be classified into fixed speed, limited variable speed and variable speed [3,4]. The fixed speed (or Type-1) generating system employs a squirrel-cage induction generator (SCIG) which is directly connected to the grid through a step-up transformer. A soft starter and shunt capacitors are usually used for smoother connection and reactive power support. A SCIG operates within a very narrow speed range (around the synchronous speed) and that is why it is considered as a fixed speed generator. The limited variable speed (or Type-2) generating system employs a wound-rotor induction generator (WRIG). The speed of the generator can be varied within a certain range by adjusting external rotor impedance of the generator. The variable speed generating system requires either partial-size or full-size converters. The generating system with partial-size converters (or Type-3) employs a doubly feed induction generator (DFIG). The rotor excitation of the DFIG is supplied by a current regulated voltage source converter, which adjusts the magnitude and phase angle of rotor current almost instantly. The rotor side converter is connected back-to-back to a grid side converter. The generating system with full-size converter (or Type-4) usually employs a permanent magnet synchronous generator (PMSG), which is connected to the grid through full size back-to-back voltage source converters or a diode rectifier and a voltage source converter.

In terms of power control, a wind turbine (WT) can be classified into stall-controlled and pitch-controlled [5,6]. A stall-controlled WT has a fixed blade angle but the blades are carefully designed to reduce aerodynamic efficiency at higher wind speeds to prevent the extraction of excessive power from the wind. On the other hand, a pitch-controlled WT adjusts the blade pitch angle to limit the power capture at higher wind speeds. Most of the earlier wind farms used fixed speed stall-controlled wind turbines [7]. A fixed speed WT is also known as "Danish concept" as it was developed and widely used in Danish wind farms. However, the present trend is to use variable speed WTs that employ DFIGs. In both cases, it is very important to incorporate the model of WTGS into existing computational tools used in power system studies.

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The steady state behavior of a power system is usually evaluated through power flow calculations which mainly determine the complex voltage (magnitude and phase angle) of all buses. The complex power flow through each branch and other quantities are then calculated using the complex bus voltages. In power flow calculations, the buses of a power system are classified into swing (or V-δ) bus, voltage-controlled (or P-V) bus and load (or P–Q) bus [8,9]. For a P–V or a P–Q bus, the active power injection P into the bus is known or specified. Fortunately, most of the WT manufacturers provide the power curve (mechanical power verses wind speed) of the turbine [10,11]. By knowing wind speed, the corresponding turbine mechanical power can immediately be determined from the curve.

In power flow analysis, a fixed speed wind generating system is usually represented by a P–Q model or an R-X model [12–16]. In P–Q model, the reactive power drawn by the generator is first approximated in terms of its active power and terminal voltage. The per-phase steady state equivalent circuit of the generator, with some approximations, is used for this purpose. For a given wind speed, the generator bus is treated as a P–Q bus with varying reactive power, in contrast to a conventional P–Q bus where it remains constant. This model may not provide correct results because of the approximations used in evaluating the reactive power. An accurate P–Q model of a SCIG is described in [16] but the model need to be evaluated as a part of the iterative process of the power flow program. A DFIG or a PMSG can also be represented by a P–Q model with varying reactive power as it is controlled by the converter. Such generators can also be operated either as constant power factor mode or constant voltage mode.

In R-X model, a SCIG generator is represented by an equivalent impedance obtained from its steady state equivalent circuit [12,13]. In power flow analysis, the impedance is then considered as a shunt element at the generator terminal bus. However, the impedance of the generator is not constant but highly dependent on operating slip which is not known *apriori*. In [12], a sub-problem is formulated to calculate the slip iteratively. Alternatively, the jacobian of the power flow program can be modified to include the slip [17]. In both cases, significant modifications to the source codes of the program are needed.

This paper proposes a simple method of incorporating the exact equivalent circuit of a fixed speed wind generator into a power flow program that does not require any modification to source codes of the program. The method simply augments the network by two internal buses of the generator to include all parameters of the exact equivalent circuit of the generator. The proposed method is then tested on a simple system as well as on the IEEE 30- and 118-bus systems.

2. Power flow method

Power flow is one of the most important computational tools used in power system operation and planning studies. It solves the active and reactive power equations to find bus voltage magnitudes and phase angles. The injected active power (P_i) and reactive power (Q_i) into bus i of an n-bus power system can be written as [8]

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

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

Here $\mathbf{Y} = (G + jB)$ and $\delta_{ij} = (\delta_i - \delta_j)$. V_i and V_j are the voltage magnitude of buses i and j, respectively. δ_i and δ_j are the voltage phase angle of buses i and j, respectively, and $\mathbf{Y}$ is the bus admittance matrix.

The Newton Raphson (NR) method is commonly used to solve the above equations. The governing equation of the method can be written as

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

The size of the jacobian matrix J in (3) is $(n_{PV} + 2n_{PQ}) \times (n_{PV} + 2n_{PQ})$, where n_{PV} is the number of P-V buses and n_{PQ} is the number of P–Q buses in the system. The computational algorithm of the method is well described in literature [8,9]. For most of the well-behaved systems, the NR method usually converges in 3–6 iterations.

3. Wind power

The mechanical power captured by a wind turbine (P_T) can be written as [18,19]

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

Here ρ is the air density (kg/m^3), A is the turbine blade swept area (m^2), V_w is the wind speed (m/s), and C_p is the performance coefficient of the turbine. C_p is a function of tip speed ratio λ and blade pitch angle β, and it can be expressed as [19]

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

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

Here ω_T and ω_r are the angular velocity (rad/s) of the turbine and the generator rotor, respectively. R is the turbine blade length (m) and a_g is the gear ratio. The value of various constants (c_1–c_9) can be determined from manufacturer data. The above equations are very useful in designing control system of a WT to maximize its efficiency. However, the objective of this paper is to determine the power flow results of a wind integrated power system and the evaluation of control strategy of WT is beyond the scope of the paper.

A typical variation of turbine power against wind speed is shown in Fig. 1 where V_{in}, V_r and V_{out} represent the cut-in wind speed, rated wind speed and cut-out wind speed, respectively,

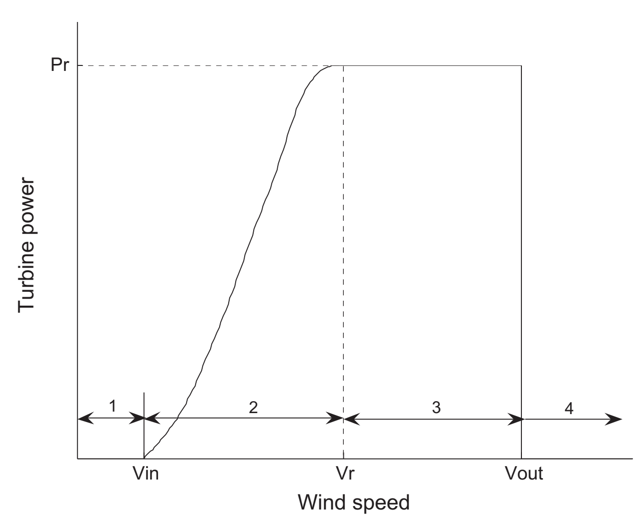

Fig. 1. Typical power curve of a wind turbine.