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Addressing and assessing the issues related to connection of the wind turbine generators to the distribution grid

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ABSTRACT

Integration of wind power generation into power distribution grid may result in stability and power quality challenges. In this way, this paper first reviews the grid integration issues of wind power generation. Then, as the main contribution, the paper develops in-depth theoretical analyses for examination the grid integration issues such as voltage rise, output power fluctuations, and static and dynamic voltage variations created due to grid integration of wind turbines and corresponding aerodynamic power fluctuations. Besides, the paper addresses these issues by proposing elaborate control approaches and by using the static compensator (STATCOM). The paper first addresses the problem of voltage rise by active power curtailment through pitch control. However, this method may result in a large waste of wind energy that may not be cost effective. Next, the STATCOM is implemented and efficient control approaches are proposed for addressing the problem of voltage rise, improvement of voltage profile and suppression of voltage and power fluctuations. At the end, simulation studies for the study distribution grid are given. The study system is an actual distribution grid in Iran with approximately 7.9 MW wind power generation and 21.9 MW load.

1. Introduction

During several years, wind turbine generators have gaining more and more attention worldwide as an alternative to large-scale central generating stations. In the early stage of wind turbine development, most wind turbines were fixed speed type. That means that regardless of the wind speed, the wind turbine's rotor speed is fixed and determined by the frequency of the supply grid, the gear ratio and the generator design. The fixed speed wind turbines are equipped with an induction generator that is directly connected to the grid, with a soft-starter and a capacitor bank for reducing reactive power compensation [1]. They are designed to achieve maximum efficiency at one particular wind speed.

The integration of wind power generation into the power grid results in technical challenges such as stability problems and power quality issues. The stability problems such as transient, small signal and frequency stability are beyond the scope of the paper.

Depending on the wind turbine technology, important power quality issues of wind power include flicker, harmonics, overvoltage, overloading, voltage and power fluctuations, increased short circuit power level and protection malfunctioning [2]. The different power quality issues have been addressed by several researchers in literatures. The flicker issue has been investigated in [3,4]. The overvoltage and overloading are the important phenomena have been addressed in [5–11], using active management remedies. The remedies include wind energy curtailment, reactive power compensation and coordinated on-load tap changer (OLTC). In [12] economic impact of power curtailment to both the hydroelectric utility and the wind power producers are identified and discussed. In [13] some problems of wind power operation are proposed in the following aspects: wind power penetration in regional grid, voltage control in regional network, the stability of power grid and the effect of HVDC system on wind power integration. In [14] the need of reserve power for power fluctuations compensation and the main particularities of wind energy integration in the Romanian power grid are presented. Paper [15] describes the actual situation of the integration of wind power in Spain and presents the actual regulation, especially on the economic incentives. A case study of the grid integration of two wind generator technologies, i.e. direct-driven synchronous generator and DFIG technologies, on a typical sub-transmission network in Namibia is studied in [16]. Paper [17] deals with the small scale integration of variable speed wind turbines and investigates the effect of reactive power control from wind turbines on the local voltage

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stability considering different types of load. In [18] transformation of the fluctuating wind generation into a base load power supply is presented by balancing the remaining differences between predicted and actual wind power generation. In [19], to address the power unbalance between wind power generation and demand, three different strategies are studied: the curtailment of the excess of wind energy, exporting the excess of wind to neighbor systems and the use of energy storage systems to absorb the power unbalances. Paper [20] deals with integrating high levels of wind in islanded systems and addresses challenges associated with the variability and uncertainty of wind power. In [21,22], power quality improvement with STATCOM for grid integration of wind energy system is presented.

Although these publications have addressed some grid integration issues of the wind turbine generators, the proposed remedies and corresponding analyses are mostly based on the simplified analytical solutions or real-time simulation. Accurately analytical analysis based research is still very rare for a number of issues in literatures.

This paper first reviews the grid integration issues of wind power generation into distribution grid. Then, as the main contribution, the paper develops in-depth theoretical analyses for examination the wind turbines grid integration issues. Next, the paper expands theoretical analyses for the elaborate control design and addresses the grid integration issues of fixed speed wind turbines by using the STATCOM.

The following issues are investigated and addressed in the paper: overvoltage/undervoltage, voltage fluctuations, and power variations. The paper first deals with the static voltage variation, dynamic power fluctuations and dynamic voltage variations in active distributions grids with wind power generation. The dynamic fluctuations in the voltage and power are created due to aerodynamic torque fluctuations of the wind turbine units. Next, the controls of static compensator (STATCOM) are developed for improvement of voltage profile and suppression of voltage variations and power fluctuations. At the end, simulation studies for the study distribution grid are given. The study system is an actual distribution grid in Iran with approximately 7.9 MW wind power generation and 21.9 MW load. For investigating the study distribution network, different conditions of the load and wind power generation are considered to take into account the possible situations of the network. Simulation studies are carried out in MATLAB-SIMULINK environment.

2. Voltage variation in distribution networks with wind power generation

It is noted that in this paper, the analyses and equations are developed based on the following conditions and assumptions:

(a) All system parameters and variables given in the paper are in per unit.
(b) The superscript, $-$, $\sim$ and $*$ denote the mean value, dynamic value and reference value, respectively, also the subscript *com* represents the variables related to STATCOM.

Conventional distribution networks without DG generation are mainly passive and the main problem in these networks is undervoltage that may occur in some situations. The use of on-load tap changers (OLTC) is a well known method of controlling the load voltages in the acceptable range. When wind turbine units are connected to the grid, they may result in overvoltage which was previously not a trouble. To learn more, Fig. 1 is considered, showing a simple network with wind farm and loads connected to the grid through a line impedance $Z_{line} = R_{line} + jX_{line}$.

In the fixed speed wind turbines, to keep the voltage within the specified limits and to minimize the power losses, generally the capacitors are installed at the terminals of induction generator. These capacitors are selected to provide the reactive power required by the induction generator. Hence, in Fig. 1, it is assumed that all wind turbine units operate at unity power factor, and thus Q_{wind} is negligible.

The wind turbine injects the active power P_w to bus 2, and the load connected at bus 2 is $P_{load} + jQ_{load}$. A close approximation for voltage drop over the line impedance Z_{line} is given by

$$\Delta V = |V_1| - |V_2| \cong R_{line}(P_{load} - P_{wind}) + X_{line}(Q_{load}) \quad (1)$$

where V_1 and V_2 are the grid and wind farm bus voltages in pu, respectively, and ΔV is the voltage drop across the line in pu. It is noted that all parameters and variables given in (1) is in per unit.

From (1), it is clear that both the active and reactive power flows affect the voltage change in a distribution network. In distribution networks, the line series resistance R_{line} cannot be neglected compared to the line series reactance X_{line}, and thus R_{line} has an important role on the overvoltage in distribution networks with high wind power penetration. In Fig. 1, while the power production by the wind power increases the voltage of bus 2 is also increases. Thus, depending on the power output from the wind farm and the network impedance between the wind farm and the substation, this may cause an overvoltage in the network. Hence, the risk of voltage rise caused by the wind turbine units is an issue for connecting of wind farms to the weak distribution grids.

3. Dynamic response of fixed speed wind turbine under aerodynamic torque fluctuation

The aerodynamic torque fluctuations in wind turbine generators are mainly created by the wind power fluctuations due to wind speed variations, wind shear and tower shadow effects [23]. In this section the impact of aerodynamic torque fluctuations due to wind shear and tower shadow effects on the dynamic behavior of fixed speed wind turbines is evaluated. The aerodynamic torque under specific wind speed can be expressed as [23]:

$$T_m = \overline{T}_m + \widetilde{T}_m \quad (2)$$

where $\overline{T}_m$ is the average torque at the operating point and $\widetilde{T}_m$ is the torque fluctuations caused by the tower shadow and wind shear effects. The aerodynamic torque fluctuation is considered to have a value proportional to $\overline{T}_m$. For wind turbines with 3 blades, the wind shear and the tower shadow effects cause 3p aerodynamic torque oscillations with frequency of ω_p. For sinusoidal aerodynamic torque oscillation, $\widetilde{T}_m$ can be given by

$$\widetilde{T}_m(t) = D_{T_m} \cos(\omega_p t) \quad (3)$$

where ω_p is given by $\omega_p = \frac{3(\omega_s - \omega_2)}{n_p \cdot n_{gear}} \omega_b$, where n_p is the number of generator pole pairs, n_{gear} is the gear box ratio, ω_2 is the slip frequency in per unit, ω_s (1 pu) is the stator frequency, and ω_b ($2\pi f_s$) is the base of angular frequency. The amplitude of mechanical power fluctuation is 10–20% of its average value [23].

The aerodynamic torque fluctuations result in fluctuations on the generator speed and slip with frequency of ω_p. In the fixed speed wind turbine, the generator output power is highly dependent on the slip, and thus the slip fluctuations result in output wind power fluctuation. Hence, the output power of the wind turbine, may be given

$$P_w = \overline{P}_w + \widetilde{P}_w \quad (4)$$

where $\overline{P}_w$ is the average output power at the operating point and $\widetilde{P}_w$ is the output power fluctuations.