Electrical Power and Energy Systems 80 (2016) 306–311

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Insertion of wind generators in electrical power systems aimed at active losses reduction using sensitivity analysis

William M. da Rosa *, Priscila Rossoni, Julio C. Teixeira, Edmarcio A. Belati

Federal University of ABC (UFABC), CECS, R. Santa Adelia, 166, 09210-170 Santo Andre, SP, Brazil

ARTICLE INFO

Article history:
Received 3 April 2015
Received in revised form 24 December 2015
Accepted 4 February 2016
Available online 16 February 2016

Keywords:
Wind energy
Sensitivity analysis
Wind generators
Incremental Transmission Losses

ABSTRACT

The study evaluates the electrical power system behaviour when wind turbines are inserted into the power grid. The assessment is made using a sensitivity analysis technique applied to the power flow solution. Unlike the typical algorithms, the sensitivity analysis technique does not require an iterative process, resulting in a fast method with great precision. This proposed method make easy to check the wind turbine behaviour to the changing of wind speed. Initially, the power flow solution is obtained and identified as the base case. When there are perturbations in the generators, the new solution is obtained directly by sensitivity analysis technique. The technique was applied in 34-bus, 70-bus and 126-bus test distribution system. The places chosen to connect the wind turbines were determined by the Incremental Transmission Losses method. The results demonstrate the effectiveness of the methodology. When wind turbines are inserted in the studied systems, active and reactive losses are reduced and voltage profile is improved.

Introduction

The development of alternative energy sources are growing in the world. Wind energy conversion takes a key role in environmental issues, being a renewable source of natural energy, clean and efficient. Wind turbines can be used both in connection with electrical grids as in isolated places [1].

Brazil has one of the largest wind potential on the planet and one of the most promising markets for wind power generation. The year 2013 was a historic year for wind energy in Brazil, being contracted 4.7 gigawatts (GW) of energy (data EPE – Energy Research Company) [2], capable of supplying energy for about 8.5 million households. Currently, there are in operation in the Northeast 21 wind farms and, in the region Southern 27 wind farms. The forecast for 2015 is the integration of 106 more parks and in 2016, more 254 parks. These data refer to the plants of the type I, which are dispatched and scheduled by the National Electric System Operator – ONS [3]. This share growing of wind generation in the Brazilian electric power matrix, especially in the Northeast and South, has led the ONS in recent years the find structural solutions and the development of models and tools to organize this generation. Even with a good generation forecast, the inherent wind intermittency does not guarantee an exact amount of generated energy.

Some homogeneity on the mean wind speed can be achieved in large wind farms. A modern wind power generation unit typically has the ability to produce between 1 and 3 MW of active power using wind turbine with a horizontal axis. Several of these units operate jointly in a wind farm. The generating capacity of the new wind farms can reach more than 100 MW [4]. In these farms, the fast power fluctuation of one turbine caused by the wind turbulence can be compensated by another one. However, even in this case, there is a power fluctuation in terms of daily period.

The doubly fed induction generator (DFIG) is usually used for wind generation. The great ability of the DFIG to control the power factor permits to separate the study of the active and reactive power flow. This work is based on the studies related to wind turbine capacity to operate with different constant power factors, only limited by the converter power connected to the wind turbine [5–7].

One of the problems of the massive use of wind power is intermittency of winds. With the growing demand and the use of alternative energy sources such as the wind, new technologies to determine the efficiency of the power system are needed. One of these technologies is the Smart Grids, a promise to be the new paradigm of the electrical industry. The Smart Grid will bring advances toward the new technologies that will enable a better electrical system management.

Because of these technological improvements in generating electrical energy from an intermittent energy source, it is essential to have an understanding on the alterations of system losses caused by wind generation. These losses are represented by

---

* Corresponding author.
E-mail address: william.moreti@ufabc.edu.br (W.M. da Rosa).

http://dx.doi.org/10.1016/j.ijepes.2016.02.002
0142-0615/

nonlinear functions, which are non-convex and not separable, not allowing direct identification of the same [8].

This work presents a study of technical losses in distribution systems caused by the wind energy, based on sensitivity analysis (SA) of load balance equations of the system [9]. It comprises a sensitivity matrix that incorporates all the parameters of the network to estimate the network parameters when there is intermittency in the power injection.

The contribution of this work is to introduce a methodology to allocate two wind farms into the power system to reduce its losses based on the Incremental Transmission Losses (ITL) and to verify the power system behaviour using the sensitivity analysis method. The ITL was used with two techniques of sensitivity analysis, one for allocating wind generators on the network and another to make the electrical system analysis of the intermittency in the power injections. The two techniques use as input data the Jacobian matrix of the system. Therefore, these techniques used together provide an efficient methodology for allocation and analysis of wind generators.

This paper is organized in various sections: Section 'Power flow equations' presents the power flow equations; Section 'Sensitivity analysis technique' describes the SA methodology; Sections 'Determination of the wind turbine power' presents the wind turbine characteristics; Section 'Incremental Transmission Losses method' describes the ITL method used to allocate the wind generators; S ection 'Methodology to integrate the SA in the ITL method' presents the developed methodology to integrate the SA into ITL method for wind generators; Section 'Results' describes the case studies; the simulation results, which demonstrate the effectiveness of the analyses. Finally, in Section 'Conclusion' the concluding remarks are presented.

Power flow equations

The active and reactive power injection are obtained from imposing the Kirchhoff's Current Law at each power system bus and can be calculated in polar form by Eqs. (1) and (2), respectively.

$$P_k(V,\theta) = V_k \sum_{m\in k} V_m (G_{km} cos\theta_{km} + B_{km} sin\theta_{km}) \tag{1}$$

$$Q_k(V,\theta) = V_k \sum_{m\in k} V_m (G_{km} sin\theta_{km} - B_{km} cos\theta_{km}) \tag{2}$$

where:

V_k – voltage magnitude at bus k.
V_m – voltage magnitude at bus m.
θ_{km} – difference in voltage phase between the k and m bus.
G_{km} – real element of the matrix Y_{BUS} associated with the bus k and m.
B_{km} – imaginary element of the matrix Y_{BUS} associated with the bus k and m.
$m \in k$ – the set of all m bus having connection with the bus k.

The solution of the Power Flow (PF) problem is obtained from the balance equations of the active and the reactive power given, respectively, by Eqs. (3) and (4).

$$\Delta P_k = P_k^{spe} - P_k^{calc}(V,\theta) = 0 \tag{3}$$

$$\Delta Q_k = Q_k^{spe} - Q_k^{calc}(V,\theta) = 0 \tag{4}$$

where *spe* superscript represents the values specified of power injections at bus that are considered constant (constant power load model) and *calc* superscript is the calculated values of power injections obtained from the vector of state variables (V,θ) and system parameters.

The Newton Raphson (NR) method [10] was implemented to solve the PF problem. This method brings a computational gain in the sensitivity analysis because it uses the data from the last iteration of the Jacobian matrix.

Sensitivity analysis technique

The high computational speed of the SA technique has great importance in studies of electrical power system operation [11]. It helps in understanding the relationship existing between cause and effect system parameters and can be used in real time applications. The proposed method incorporated this technique to calculate the effect of the wind intermittency in the power systems voltage.

Two types of variables are considered in this study: operating variables denoted by the vector u; and controlled variables denoted by the vector x, where:

x – state variables vector (V,θ).
u – active and reactive power injection vector (P_k^{esp}, Q_k^{esp}).

The active and reactive power flow equations, Eqs. (3) and (4) can be written compactly as:

$$g(x,u) = 0 \tag{5}$$

Considering that $x = x^*$ is the solution to the vector control specified $u = u^*$ that satisfies Eq. (5), then:

$$g(x^*,u^*) = 0 \tag{6}$$

As a modification Δu in u^* causes a change Δx in x^*, the expansion in Taylor's Series of (6) until first order term gives us the Eq. (7).

$$g(x^* + \Delta x, u^* + \Delta u) \cong g(x^*,u^*) + S_x\Delta x + S_u\Delta u \tag{7}$$

The S_x is the system Jacobian matrix (J), the same obtained in the NR last iteration as follows:

$$S_x = J = \begin{bmatrix} \frac{\partial\Delta P}{\partial\theta} & \frac{\partial\Delta P}{\partial V} \\ \frac{\partial\Delta Q}{\partial\theta} & \frac{\partial\Delta Q}{\partial V} \end{bmatrix} \tag{8}$$

The S_u matrix is obtained by Eq. (9).

$$S_u = \begin{bmatrix} \frac{\partial\Delta P}{\partial P} & \frac{\partial\Delta P}{\partial Q} \\ \frac{\partial\Delta Q}{\partial P} & \frac{\partial\Delta Q}{\partial Q} \end{bmatrix} \tag{9}$$

The S_u matrix results in the identity matrix, when considering constant power load model, which is the model adopted in this paper.

The combination of Eqs. (5) and (7) gives us:

$$S_x\Delta x + S_u\Delta u = 0 \tag{10}$$

Rearranging Eq. (10), one can obtain the correction Δx vector:

$$\Delta x = -S_x^{-1} S_u \Delta u \tag{11}$$

As S_u is the identity matrix and S_x^{-1} is equal to J^{-1}, the expression for the correction vector Δx is given by:

$$\Delta x = J^{-1}\Delta u \tag{12}$$

The Eq. (12) can be written in matrix form as (13), wherein NPQ is the number of load bus of the distribution system.

$$\begin{bmatrix} \Delta x_1 \\ \Delta x_2 \\ \vdots \\ \Delta x_{(2NPQ)} \end{bmatrix}_{(2NPQ)} = \begin{bmatrix} \frac{\partial\Delta P}{\partial\theta} & \frac{\partial\Delta P}{\partial V} \\ \frac{\partial\Delta Q}{\partial\theta} & \frac{\partial\Delta Q}{\partial V} \end{bmatrix}^{-1}_{(2NPQ\times 2NPQ)} \begin{bmatrix} \Delta u_1 \\ \Delta u_2 \\ \vdots \\ \Delta u_{(2NPQ)} \end{bmatrix}_{(2NPQ)} \tag{13}$$