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Voltage control settings to increase wind power based on probabilistic load flow

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Abstract

In this paper, network constrained setting of voltage control variables based on probabilistic load flow techniques is presented. The method determines constraint violations for a whole planning period together with the probability of each violation and leads to the satisfaction of these constraints with a minimum number of control corrective actions in a desired order. The method is applied to define fixed positions of tap-changers and reactive compensation capacitors for voltage control of a realistic study case network with increased wind power penetration. Results show that the proposed method can be effectively applied within the available control means for the limitation of voltages within desired limits at all load buses for various degrees of wind power penetration.

Keywords: Distributed generation; Probabilistic load flow; Constrained load flow; Sensitivity analysis; Voltage control

1. Introduction

Connection rules and criteria applied nowadays to the penetration of Distributed Generation (DG) are based on deterministic steady state analysis. In general, the approach adopted is to ensure that any new generation does not reduce the quality of supply offered to other customers and to consider the generators as 'negative load'. As the network operator has no control over the dispersed generator all decisions concerning the network are made considering the worst possible conditions of the generation for any set of network conditions. Hence at minimum load, maximum generation and at maximum load, minimum generation is assumed. Using deterministic load flow analysis however, it is not possible to assess objectively how often and where overvoltages or undervoltages occur in the network during a whole study period, since it is based on selected combinations of consumer loads and DG power production. As shown in [1], this can be achieved by applying probabilistic techniques like the probabilistic load flow (PLF) or the Monte Carlo simulation. PLF requires modeling of loads and power productions as probability density functions and provides the complete spectrum of all probable values of the bus voltages and power flows in the study period with their respective probabilities taking into account generation and load uncertainties and correlations and topological variations. The probabilistic load flow was analytically formulated since more than 25 years in [2,3], and further developed and applied in [4–10]. This paper investigates the application of PLF techniques to the adjustment of voltage control settings in order to allow increased penetration of wind power in weak parts of a network. A method for network constrained setting of control variables based on PLF was presented in [11] and applied to distribution voltage control [12], voltage collapse analysis [13] and generator reactive power optimization [14]. Accordingly, once the probabilities of constraint violations are obtained from PLF, an iterative method is employed which provides adjustments of the control variables based on sensitivity analysis of the constrained variables with respect to the control variables, while maintaining constraints already satisfied within limits. The basic advantage of the method is that it provides increased flexibility in the selection of the control variables to be varied. Thus, application of the proposed method can lead to satisfaction of constraints with a minimum number of control variables adjusted or corrective actions on control devices in a desired order.

In this paper, the above constrained probabilistic load flow (CPLF) method is applied to the setting of fixed positions of

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tap-changers and reactive compensation devices in order to increase wind power penetration in a weak part of the Hellenic power system that presents high interest for wind farm installations. The results show that the proposed method can be effectively applied within the available control means for the limitation of voltages within desired limits at all buses for the whole planning period considered even if high wind power penetration is allowed.

2. Constrained probabilistic load flow

2.1. Fundamentals of probabilistic load flow

The load flow problem can be expressed mathematically by two sets of non-linear equations:

$$Y = g(X, U), \qquad Z = h(X, U) \tag{1}$$

Y is the input, Z the output, X the state and U the control vector. The input vector Y comprises nodal power injections, the state vector X voltage magnitudes and angles, the output vector Z power flows, generation reactive injections, etc. and the control vector U the control means of the system like transformer taps, reactive compensation, voltages and active production at PV buses, etc. Probabilistic modelling of production takes into account generator outages and wind power uncertainties, while probabilistic distributions of demands are obtained from load time series analysis. Thus, PLF provides the complete spectrum of all probable values of state and output variables, each value with its respective probability taking into account generating unit unavailabilities, load uncertainties, dispatching criteria effects and topological variations.

Most of the techniques developed for PLF are based on the linearization of (1) around an expected operating point defined by X_o, U_o.

$$X = X_o + J^{-1} Y \tag{2}$$

where

$$J = \frac{\vartheta g(X, U)}{\vartheta X} \tag{3}$$

is the Jacobian of the system.

After linearization, the output vector elements are expressed as linear functions of the nodal active and reactive power injections, defined by probability density functions, as:

$$Z = Z_o + A^{\mathrm{T}} Y \tag{4}$$

The weighting coefficients of these linear functions are the sensitivity coefficients obtained from matrix:

$$A^{\mathrm{T}} = \left(\frac{\vartheta h(X, U)}{\vartheta X}\right)^{\mathrm{T}} \cdot \left(\frac{\vartheta g(X, U)}{\vartheta X}\right)^{-1} \tag{5}$$

Convolution techniques and the Fast Fourier Transform are used to deduce the unknown probability functions of the state and output variables.

The objective of constrained load flow is to maintain some or all the elements of X and Z within given operating limits. Such constraints are normally set to voltage magnitudes of load buses, active and reactive powers injected at generator buses, apparent power flows on lines, etc. Operation within constraints can be achieved by appropriate variation of the control variables U, which are also constrained, i.e. physical limits constrain the variation of transformer taps, shunt compensation devices, voltages at PV buses, etc.

In the general case, an unconstrained load flow solution would result in a number of variables in X and Z falling outside their permissible variation interval. In order to limit those variables, action on the control variables is required. This action can be based on the results of sensitivity analysis, i.e. calculation of the sensitivity factors of every variable that needs to be constrained with respect to the control variables.

2.2. Sensitivity analysis

Consider a network of n buses and m control variables and

$$W = f(X, U) \tag{6}$$

the set of non-linear functions of the r variables to be constrained. f includes a selected number of the functions denoted by g and h in (1). Linearization of f at a given operating point defined by $U = U_o$ and $X = X_o$ gives:

$$f(X, U) = f(X_0, U_0) + \sum_{j=1}^{m} \frac{\mathrm{d}f(X, U)}{\mathrm{d}u_j} \Delta u_j \tag{7}$$

Sensitivity analysis assuming $\Delta Y = 0$, provides:

$$\frac{\mathrm{d}f(X, U)}{\mathrm{d}u_j} = \frac{\vartheta f(X, U)}{\vartheta u_j} - \left[\frac{\vartheta f(X, U)}{\vartheta X}\right]^{\mathrm{T}} \left[\frac{\vartheta g(X, U)}{\vartheta X}\right]^{-1} \left[\frac{\vartheta g(X, U)}{\vartheta u_j}\right] \tag{8}$$

or

$$C = D - A^{\mathrm{T}} B \tag{9}$$

Matrix C has dimension r times m, where r the number of variables to be constrained and m the number of the control variables and consists of the elements:

$$c_{ij} = \frac{\mathrm{d}w_i}{\mathrm{d}u_j} = \frac{\mathrm{d}f_i(X, U)}{\mathrm{d}u_j} \tag{10}$$

A^{T} is the sensitivity matrix (5) obtained during calculation of the probability density function of f and needs to be recalculated at each iteration based on the updated elements of the Jacobian. Thus, calculation of vector C requires only calculation of D which depends on function f and on the control variables u_j, and the calculation of B which is independent of f and depends only on control variables u_j. Suppose now that $f_{pi}(X,U)$ is the probability density function of the random variable w_i that has to be constrained and $f\min_i$,$f\max$ the extreme values of the probability density function obtained from PLF, as described above. Given the upper and lower limit of the interval where this vari-able is allowed to vary, $w\min_i$