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Reactive power rescheduling with generator ranking for voltage stability improvement

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A B S T R A C T

In a power system, voltage stability margin improvement can be done by regulating generators voltages, transformers tap settings and capacitors/reactors rated reactive powers (susceptances). In this paper, one of these methods, which we name "reactive power rescheduling with generator ranking", is considered. In this method, using "ranking coefficients", the generators are divided into "important" and "less-important" ones and then, voltage stability margin is improved by increasing and decreasing reactive power generation at the important and less-important generators, respectively. These ranking coefficients are obtained using "modal analysis". In this paper, the method's performance for two types of ranking coefficients has been analyzed. Also, for comparison purpose, the "usual form of optimal reactive power dispatch" method has been simulated. For all simulations, the IEEE 30 bus test system has been used. The simulation results show that in the former method, for either type of ranking coefficients, voltage stability margin is considerably improved and, usually, the system active loss and the system operating cost are increased. Also, in the latter method, voltage stability margin is improved and the system active loss and the system operating cost are decreased.

1. Introduction

The transfer of power through a transmission network is accompanied by voltage drops between the generation and consumption points. In normal operating conditions, these drops are in the order of a few percents of the nominal voltage. One of the tasks of power system planners and operators is to check that under heavy stress conditions and/or following credible events, all bus voltages remain within acceptable bounds. In some circumstances, however, in the seconds or minutes following a disturbance, voltages may experience large and progressive falls, which are so pronounced that the system integrity is endangered and power cannot be delivered correctly to customers. This catastrophe is referred to as voltage instability and its calamitous result as voltage collapse. This instability stems from the attempt of load dynamics – especially loads supplied with under load tap changing transformers (ULTC), induction motors and thermostatic loads – to restore power consumption beyond the amount that can be provided by the combined transmission and generation system [1]. Nowadays, there are some voltage stability criteria being implemented. For example, the Western Electricity Coordinating Council (WECC) proposes a minimum voltage stability margin (VSM) requirement of 5% considering simple contingencies, 2.5% for double contingencies, and larger than zero for multiple contingencies. In a similar way, the ONS (Brazilian System Operator) has also initiated some studies and recommends a minimum VSM requirement of 6% also considering simple contingencies. Both criteria are based on VSM index, which is obtained from PV curve computations and represents the distance from the current operating point to the voltage stability limit [2].

"Reactive power management" is the general name of methods which try to improve voltage profile/stability by regulating generators voltages, transformers tap settings, reactive sources settings and installing new reactive sources. These methods can be divided into two areas: reactive planning (allocation) and reactive dispatch (re-dispatch, scheduling, rescheduling). Also, the dispatch area can be divided into two areas: off-line reactive dispatch and on-line reactive dispatch. In the reactive planning area, the period of study is the next few months or the next few years and installing the new reactive sources are also considered. In the off-line reactive dispatch area, only installed reactive sources are used and the period of study is the next few days or the next few hours. In the on-line reactive dispatch area, only installed reactive sources are used and the period of study is the next few minutes or the next few seconds [3].

In the off-line reactive dispatch area, voltage profile/stability improvement is done by regulating generators voltages, transformers tap settings and capacitors/reactors rated reactive powers (susceptances). For this purpose, usually two groups of methods are used. In the first group methods – which are referred by names such as "optimal reactive power dispatch", "reactive power optimization", etc. – a specific optimization problem with specific

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Nomenclature

N_B	set of numbers of total buses
N_0	set of numbers of total buses, excluding slack bus
N_i	set of numbers of buses adjacent to bus *i*, including bus *i*
N_G	set of numbers of generator buses, including slack bus
N_{PQ}	set of numbers of load buses
N_C	set of numbers of shunt capacitor/reactor installation buses
N_E	set of numbers of system branches
N_T	set of numbers of tap changing transformer branches
n_G	number of system generators
R_k, X_k	resistance and reactance of branch *k* (pu)
Q_{ci}	rated reactive power (susceptance) of shunt capacitor/reactor at bus *i* (pu)
T_k	transformer tap setting of branch *k*
G_{ij}, B_{ij}	mutual conductance and susceptance between buses *i* and *j* (pu)
V_i	voltage magnitude of bus *i* (pu)
θ_i	voltage angle of bus *i* (rad)
θ_{ij}	voltage angle difference between buses *i* and *j* (rad)
P_i, Q_i	injected active and reactive power at bus *i* (pu)
P_{gi}, Q_{gi}	generated active and reactive power at bus *i* (pu)
S_k	apparent power flow in branch *k* (pu)
P_{Loss}	system active loss (pu)
Cost	system operating cost (unit of money per hour)

objective function(s) and specific constraints is defined and then, by solving this problem (using an optimization algorithm), appropriate values for those quantities are obtained [4–9]. In the usual form of these methods, voltage profile/stability improvement is done by minimizing the system active loss [4,5]. In the second group methods – which do not have an accepted name – initiative algorithms are used [10–13].

In this paper, a method from the second group is considered. In this method, which we name "reactive power rescheduling with generator ranking", using "ranking coefficients", the generators are divided into "important" and "less-important" ones and then, voltage stability margin is improved by increasing and decreasing reactive power generation at the important and less-important generators, respectively [12,13]. These ranking coefficients are obtained using "modal analysis" [14–16]. In [12,13], this method has been used by selecting a specific type of ranking coefficients. But, in this type of ranking coefficients, there is no coefficient related to the slack bus generator. Thus, the reactive power generation of the slack bus generator has not been used effectively. Also, in these references, the effect of "weighting factor" on the method's performance has not been studied. In this paper, first, the modal analysis theory is presented in a new and clear form. Then, the "reactive power rescheduling with generator ranking" method is simulated by selecting two types of ranking coefficients (which one of them presents ranking coefficients for "all" generators including the slack bus generator). Also, the effect of "weighting factor" on the method's performance is studied. In addition, for comparison purpose, the "usual form of optimal reactive power dispatch" method is also simulated. For all simulations, the IEEE 30 bus test system is used.

2. Modal analysis

Modal analysis is a method for voltage stability evaluation. In this method, voltage stability analysis is done by computing eigenvalues and right and left eigenvectors of a jacobian matrix (which is obtained from the power flow equations). At an operating point, the relations between main power system quantities (bus voltage magnitude, bus voltage angle, bus active power and bus reactive power) can be expressed by power flow equations as follows:

$$\begin{pmatrix} P_s \\ P_g \\ P_L \\ Q_L \\ Q_{Glim} \\ Q_{Gunlim} \end{pmatrix} = f \begin{pmatrix} \theta_s \\ \theta_g \\ \theta_L \\ V_L \\ V_{Glim} \\ V_{Gunlim} \end{pmatrix} \tag{1}$$

where *s*, *g* and *L* are indices for slack bus, all generator buses except slack bus and load buses, respectively. Also, *Glim* is an index for generator buses on which reactive power generation at primary operating point is equal to lower or upper limit. In addition, *Gunlim* is an index for generator buses on which reactive power generation at primary operating point is within lower and upper limits. Finally, *f* is a function that relates power system main quantities to each other and, in other words, is a symbol of power flow equations. After linearization of power flow equations, depending on equations which contribute in the linearization and quantities which their variations are considered equal to zero, 4 jacobian matrixes (J_{Large}, J_{Medium}, J_{Small} and J_{PF}) are obtained. Full linearization of power flow equations leads to

$$\begin{bmatrix} \Delta P_s \\ \Delta P_g \\ \Delta P_L \\ \Delta Q_L \\ \Delta Q_{Glim} \\ \Delta Q_{Gunlim} \end{bmatrix} = J_{Large} \begin{bmatrix} \Delta\theta_s \\ \Delta\theta_g \\ \Delta\theta_L \\ \Delta V_L \\ \Delta V_{Glim} \\ \Delta V_{Gunlim} \end{bmatrix} \tag{2}$$

where J_{Large} is the large jacobian matrix. Also, by removing the equation related to P_s from (1) and assuming $\Delta\theta_s = 0$, linearization of (1) leads to

$$\begin{bmatrix} \Delta P_g \\ \Delta P_L \\ \Delta Q_L \\ \hline \Delta Q_{Glim} \\ \Delta Q_{Gunlim} \end{bmatrix} = J_{Medium} \begin{bmatrix} \Delta\theta_g \\ \Delta\theta_L \\ \Delta V_L \\ \hline \Delta V_{Glim} \\ \Delta V_{Gunlim} \end{bmatrix} = \left[\begin{array}{c|c} J_1 & J_2 \\ \hline J_3 & J_4 \end{array}\right] \begin{bmatrix} \Delta\theta_g \\ \Delta\theta_L \\ \Delta V_L \\ \hline \Delta V_{Glim} \\ \Delta V_{Gunlim} \end{bmatrix} \tag{3}$$

where J_{Medium} is the medium jacobian matrix. Also, by removing the equations related to Q_{Gunlim} from (1) and assuming $\Delta V_{Gunlim} = 0$, linearization of (1) leads to

$$\begin{bmatrix} \Delta P_s \\ \Delta P_g \\ \Delta P_L \\ \Delta Q_L \\ \Delta Q_{Glim} \end{bmatrix} = J_{Small} \begin{bmatrix} \Delta\theta_s \\ \Delta\theta_g \\ \Delta\theta_L \\ \Delta V_L \\ \Delta V_{Glim} \end{bmatrix} \tag{4}$$

where J_{Small} is the small jacobian matrix. Finally, by removing the equations related to P_s and Q_{Gunlim} from (1) and assuming $\Delta\theta_s = 0$ and $\Delta V_{Gunlim} = 0$, linearization of (1) leads to