

Reactive Power Generation Management for the Improvement of Power System Voltage Stability Margin*

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Abstract - Voltage stability margin (VSM) of the power system relates to the reactive power reserves in the network. This paper presents a method to improve the VSM by generator reactive power generation rescheduling. The management of the var generation formulated as an optimization problem and pseudo-gradient evolutionary programming (PGE) was used to obtain the optimal solution. Modal analysis technique was used to guide the searching direction. Simulation results on the New England 39-bus system demonstrate that the proposed method is effective. Compared with the standard evolutionary programming (SEP), better solution can be obtained, and the convergence speed of the algorithm is improved also. The simulation results show that after the optimal reactive power rescheduling the reactive power reserves of the system is increased and the active/reactive power losses are decreased. The most important advantage is that, the voltage stability margin of power system can be improved without adding new var compensation equipment and changing the active power distribution.

Index Terms – Power system, Voltage stability margin, Pseudo-gradient evolutionary programming, Modal analysis.

I. INTRODUCTION

In recent years, much attention has been attracted to the problems of voltage stability for the electric power systems. Because of the continuous increase of power demands and large scale system interaction as well as the consideration of both the economic benefits and the environment protection, modern power systems are operated more and more close to their maximum operation conditions. Under such conditions, voltage instability of the systems likely occurs, which will, then, heavily threaten the stable operation of overall power systems. Power system voltage instability may be initiated by a disturbance or an accident under the conditions that are usually characterized by shortage of reactive power reserves. Hence, voltage stability of power systems has been closely linked with the reactive power reserves of the systems. As voltage collapse is associated with the fact that the reactive power demands is not able to met due to the limitations of the production and the transmission of the reactive power, the amount of reactive power reserves at generating stations can be used as a measure for the power system voltage stability. Over the years, system operators have relied on generator var reserves to gauge the voltage stability level of a power system.

The reactive power reserves of the key generators in the grid are also used by some practical equipment for online voltage stability monitoring [1].

The understanding of the power system voltage stability relating to dynamic var reserves has led to the following research efforts on this subject. The relationship of reactive power reserves and VSM is quantitatively analyzed in [1]. In [2] the voltage stability criteria is met by simultaneously changing the active and reactive power distribution, which will have great influence on the system operation scheme. In [3], the reactive generations are rescheduled to improve the voltage stability. However, in this research, the active power losses were not considered and obviously the solution can not be the optimum.

This paper proposed a new method for the management of the reactive power reserves. In the proposed method, the management of the reactive power reserves is processed as an optimization problem. The main objective of the optimization is to increase the reactive power reserves as well as to decrease the active power losses by rescheduling the reactive power injection of the generator units. As a result, the voltage stability margin will be improved with no negative impact on the active economical dispatch. The optimization problem is solved with a pseudo-gradient evolutionary programming algorithm, which incorporates the advantages of evolutionary programming in finding out the global optimal solution and the gradient method in increasing the convergence speed. The optimal solution is searched in the direction provided by the modal participation factors calculated for generator units. Simulation results show that the proposed method is effective. The system reactive power reserves as well as the voltage stability margin were improved and the active power losses were decreased.

II. REACTIVE POWER RESERVES OPTIMIZATION

A. Mathematic Model of the Objective Function

As has been mentioned in the previous section the voltage stability of a power system can be represented, in some way, by the voltage stability margin. The voltage stability margin is usually measured by the distance in MW or percentage between the current operating point and the maximum operating point (corresponding to the nose point of PV curve). Giving a load increasing mode and a generation distributing

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mode, the PV curve can be acquired by continuous load flow method. This method is used in the current research to calculate the PV curve and then the voltage stability margin.

The modal analysis on generators indicates that voltage stability can be improved by regulating the reactive power generations along the direction guided by the active participation factor (APF) of each generator in the power networks. According to this principle, the objective function of this optimization problem should contain two parts: maximizing the reactive power reserves (equal to minimize the var generations) and minimizing the active power losses. Therefore, the following objective function is obtained. It should be pointed out that in the objective function given in (1), maximizing the reactive power reserves has been changed to minimizing the reactive power generation of generator units

$$F = \text{Min}(W_1 \sum Q_{Gi} + W_2 P_{LOSS}) \quad (1)$$

where Q_{Gi} is the reactive power generation of the i th generator, $i=1,2,\dots,N_G$, N_G is the number of generator units in the system; W_1, W_2 are the weight factors; P_{LOSS} is the total active power loss in the network.

The constraints to the above mention optimization are given as following

$$\begin{cases} P_i = V_i \sum_{j=1}^N V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \\ Q_i = V_i \sum_{j=1}^N V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \end{cases} \quad i \in N \quad (2)$$

$$V_{i\max} > V_i > V_{i\min} \quad i \in N \quad (3)$$

$$Q_{Gi\max} > Q_{Gi} > Q_{Gi\min} \quad i \in N_G \quad (4)$$

$$T_{i\max} > T_i > T_{i\min} \quad i \in N_T \quad (5)$$

Equation (2) is the power flow equations, where P_i and Q_i are the active/reactive power injected into network at bus i ; G_{ij} and B_{ij} represent the corresponding elements of the admittance matrices; θ_{ij} is the voltage angle difference between bus i and j ; V_i and V_j are the voltage amplitude at bus i and j ; N is the number of buses in the network. Equation (3), (4) and (5) are the maximum and minimum constraints for the voltage at bus i , the reactive power injection of the i th generator and the tap position of the i th transformer. N , N_G and N_T are the number of the bus, the generator units and the tap changed transformers in the power network.

B. Pseudo-gradient Evolutionary Programming

The objective function given in (1) shows that this is a mixed optimization problem in nature and the traditional gradient based optimal searching methods may not very efficient in processing such problem. However, recent research results show that application of evolutionary algorithms (EAs) provides an effective way to process the mixed optimization issues [4]. EAs are basically probabilistic searching methods and show excellent robustness in finding out the optimal solution. However, the standard evolutionary programming needs much calculating time for the convergence which greatly limits its application. On the other hand, the gradient based optimization methods have the

advantage of fast convergence speed, although the local optimal solution may be obtained when the multiple peak values exist for the objective functions. Recent research result indicates that both advantages of rapid convergence and the global optimal solution searching can be acquired by incorporating the SEP with the gradient based methods [5].

1) *Pseudo-Gradient*: For an n -dimensional parameter optimization problem, the conventional gradient \vec{g} of the objective function f is defined as an n -dimensional vector if the objective function is differentiable

$$\vec{g}(\vec{x}) = \nabla f(\vec{x}) = \left(\frac{\partial f}{\partial x_1}, \frac{\partial f}{\partial x_2}, \dots, \frac{\partial f}{\partial x_n} \right)^T \quad (6)$$

Gradient \vec{g} gives the information about the direction along which the objective function will be changed with the fastest speed. This is a very important feature of the gradient methods. Using this feature, the pseudo-gradient \vec{g}_p is defined as following:

a) When $f(\vec{x}_k) < f(\vec{x}_{k-1})$, searching likes a ‘‘down hill’’ move and the direction of the move from \vec{x}_{k-1} to \vec{x}_k is defined as positive and the pseudo-gradient $\vec{g}_p(\vec{x}_k)$ is defined as follow

$$\vec{g}_p(\vec{x}_k) = (\text{dir}(x_{k,1}), \text{dir}(x_{k,2}), \dots, \text{dir}(x_{k,n}))^T \quad (7)$$

Where

$$\text{dir}(x_{k,i}) = \begin{cases} 1 & x_{k,i} > x_{k-1,i} \\ 0 & x_{k,i} = x_{k-1,i} \\ -1 & x_{k,i} < x_{k-1,i} \end{cases} \quad i = 1, 2, \dots, n \quad (8)$$

b) When $f(\vec{x}_k) \geq f(\vec{x}_{k-1})$, searching likes an ‘‘up hill’’ move and the direction of the move is defined as negative and the pseudo-gradient is defined as

$$\vec{g}_p(\vec{x}_k) = 0 \quad (9)$$

In the same way that the conventional gradient method yielding points toward a solution, the pseudo-gradient is able to identify a good search direction based on the latest two points in the search space. From the definition given above, we can see that if $\vec{g}_p(\vec{x}_k) \neq 0$ a better solution of the minimization problem would be found at the next step by following the direction indicated by $\vec{g}_p(\vec{x}_k)$. Otherwise, the search direction at the point should be changed; in this situation, a randomly selected direction is used. The advantage of the pseudo-gradient is that it gives a good search direction without requiring the objective function to be differentiable. If \vec{g}_p is implemented in EA, an EA will still be problem-independent, which is an important feature of EA applications.

2) *PGEP*: In SEP, a ‘‘child’’ is generated from its ‘‘parent’’ by mutation. The mutation process is performed on each individual as follows:

$$\vec{x}'_{(k+m),i} = \vec{x}'_{k,i} + N(0, \sigma'_k) \quad (i=1, \dots, n; k=1, \dots, m) \quad (10)$$

Where $\vec{x}'_{k,i}$ is the i th element of the parent \vec{x}'_k , the k th individual in the population of the n th generation, m is the population size, $N(0, \sigma'_k)$ is a Gaussian distribution variable

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