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Voltage stability constrained dynamic optimal reactive power flow based on branch-bound and primal–dual interior point method

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ABSTRACT

A day-ahead voltage stability constrained dynamic optimal reactive power flow (VSC-DORPF) model is proposed in this paper. The amount of dynamic reactive power reserves (DRPR) is used as a measure of voltage stability of power system. The effective dynamic reactive power reserves (EDRPR) of reactive power sources are calculated to obtain DRPR of each area and the maximum variations in reactive power generation under contingency are taken as the required minimal DRPR for each area. Then the DRPR are introduced into the VSC-DORPF model as one of multiple objective functions and constraints in order to enhance the voltage stability of power system. A hybrid method, integrated by branch-bound method and primal–dual interior point (PDIP) method, is proposed to solve this VSC-DORPF problem. The discrete control variables and the time coupled constraints are handled by the proposed branching and pruning principles. As a result, the VSC-DORPF problem is decomposed into a series of optimal reactive power flow (ORPF) problems with continuous control variables only. Numerical tests with IEEE 30-bus system and IEEE 118-bus system show that the proposed model and method are effective.

Introduction

Dynamic optimal reactive power flow (DORPF) determines the proper settings of reactive power control devices in next day based on the day-ahead load forecast and active power scheduling plan in order to reduce the daily network losses, enhance voltage profile and avoid excessive operation.

As voltage stability has not been taken into account in the general DORPF model, the scheduling results cannot respond to the impact which acute load fluctuation bring to power system. A fuzzy membership function of bus voltage was taken as one of optimization objectives to increase voltage quality in [1]. However, keeping bus voltages within qualified ranges simply cannot maintain voltage stability. Thus it is necessary to carry out further researches on DORPF considering voltage stability. Dynamic reactive power reserves (DRPR) have always been linked with voltage stability as they have a significant effect on the reliable operation of power system [2]. In [3] an optimal reactive power flow (ORPF) model with DRPR of power system being one of objective functions was proposed. It is worth noting that since each reactive power source gives a different impact on the entire system, DRPR of large system cannot be obtained by merely summing up individual reserves. Thus the network was partitioned into several areas and the reactive power sources were assigned weighting factors based on the reactive power load margin of each area in [3]. But it is unreasonable to give the same factors to the reactive power sources in an area. Moreover, it cannot be guaranteed that there are sufficient DRPR in each area to maintain voltage stability merely by the weighted sum of individual reserves in objective functions without any explicit constraints.

On the other hand, DORPF problem is essentially a large scale mixed integer nonlinear programming problem. The presence of a large number of discrete control variables and time coupled constraints makes it difficult to solve. Different methods have been proposed and they can be classified basically into four categories. (1) Simultaneous solution method [4]. The operation limits of control devices are described by the analytic mathematic expressions of their control variables. The DORPF problem is solved as a whole and the discrete control variables achieve their discrete values by an embedded algorithm. Although this method usually shows good performance on small test systems, its application on larger power system will be hard. (2) Modern intelligent algorithm [1,5]. The control variables in the whole day are encoded into an individual and a modern intelligent algorithm is adopted to solve the problem. This kind of algorithm cannot be put into practical application because of its stochastic nature. (3) Decomposition coordination

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method [6,7]. The entire problem is decomposed into two sub-problems with only continuous control variables or discrete control variables respectively which interact through a coordination technology. But the independent solution of continuous and discrete variables will lead to a deviation in the search path of solution. (4) Heuristic algorithm [8,9]. The dynamic problem is converted to a series of static ones by determining an operation sequence of each control device by some heuristic rules. However, it is difficult to achieve reasonable settings of control devices by the assumed operation time.

In view of the above, a new DORPF model considering voltage stability is presented in this paper. The DRPR are taken as an index of voltage stability and they appeared in both optimization objective functions and constraints of the proposed model. It can reduce daily network losses, improve voltage quality and enhance voltage stability of power system. On the other hand, considering the two difficulties in solving DORPF problem are both related to discrete control variables, a hybrid method combined by branch-bound method and primal–dual interior point (PDIP) method is adopted to solve the problem. Branch-bound method [10] is used to solve integer programming problem and PDIP method [11] is used to solve nonlinear programming problem. The two methods are often integrated together to solve mixed integer nonlinear programming problem, such as ORPF [12,13] and unit commitment [14]. During the solution process of DORPF problem, the discrete control variables achieve discrete values via a branch-bound tree and the time coupled constraints are met by reasonable branching and pruning principles. Numerical tests with IEEE 30 and 118-bus system show that the proposed model and method are effective.

The problem formulation of VSC-DORPF

In this paper, daily active power losses, voltage deviation and DRPR of power system are taken as objective functions to reduce network losses, improve voltage quality and voltage stability. The DRPR of each area are kept larger than their required values in constraints for the purpose of mitigating voltage collapse. The proposed VSC-DORPF model can be presented as follows.

Objective functions

$$\min \sum_{t=1}^{N_T}\left[\omega_1 \frac{P_{loss}^t}{f_1^t} + \omega_2 \frac{\sum_{i=1}^{N_B}\left(V_i^t - V_{i,set}\right)^2}{f_2^t} - \omega_3 \frac{\sum_{j=1}^{N_G}\left(Q_{g,j,eff}^t - Q_{g,j}^t\right)}{f_3^t}\right] \tag{1}$$

where N_T is the number of intervals, N_B and N_G are the number of buses and generators, ω_1, ω_2 and ω_3 are the weighting factors of optimization objectives, the first objective component is daily network losses, P_{loss}^t is the active power losses at interval t, the second component is voltage deviation, V_i^t is the voltage magnitude of bus i at interval t, $V_{i,set}$ is the expected voltage magnitude of bus i, the third component is DRPR of power system, $Q_{g,j}^t$ and $Q_{g,j,eff}^t$ are the reactive power output and its effective limit of generator j at interval t, f_1^t, f_2^t and f_3^t are the optimal value of each optimization objective when optimized only at interval t respectively.

Constraints

1. Power flow equations

$$g^t(\mathbf{x}^t) = 0 \quad t = 1,\ldots,N_T \tag{2}$$

2. Operation constraints

$$V_{i,\min} \leqslant V_i^t \leqslant V_{i,\max} \quad i = 1,\ldots,N_B,\ t = 1,\ldots,N_T \tag{3}$$

3. The constraints of DRPR for each area

$$\sum_{j=1}^{N_{G,k}}\left(Q_{g,j,eff}^t - Q_{g,j}^t\right) \geqslant Q_{rs,k,\min}^t \quad k = 1,\ldots,N_{area}\ t = 1,\ldots,N_T \tag{4}$$

4. The constraints of control variables

$$Q_{g,i,\min} \leqslant Q_{g,i}^t \leqslant Q_{g,i,\max} \quad i = 1,\ldots,N_G,\ t = 1,\ldots,N_T \tag{5}$$

$$K_{i,\min} \leqslant K_i^t \leqslant K_{i,\max} \quad i = 1,\ldots,N_K,\ t = 1,\ldots,N_T \tag{6}$$

$$Q_{c,i,\min} \leqslant Q_{c,i}^t \leqslant Q_{c,i,\max} \quad i = 1,\ldots,N_c,\ t = 1,\ldots,N_T \tag{7}$$

5. Time coupled constraints

Constrains of maximum allowable action range between successive intervals:

$$|K_i^t - K_i^{t-1}| \leqslant S_{k,i,\Delta} K_{i,step} \quad i = 1,\ldots,N_K,\ t = 1,\ldots,N_T \tag{8}$$

$$|Q_{c,i}^t - Q_{c,i}^{t-1}| \leqslant S_{Qc,i,\Delta} Q_{c,i,step} \quad i = 1,\ldots,N_c,\ t = 1,\ldots,N_T \tag{9}$$

Constrains of maximum allowable action number in a day:

$$\sum_{t=1}^{N_T}\left(K_i^t \oplus K_i^{t-1}\right) \leqslant S_{k,i,\max} \quad i = 1,\ldots,N_K \tag{10}$$

$$\sum_{t=1}^{N_T}\left(Q_{c,i}^t \oplus Q_{c,i}^{t-1}\right) \leqslant S_{Qc,i,\max} \quad i = 1,\ldots,N_c \tag{11}$$

where $V_{i,\max}$ and $V_{i,\min}$ are voltage limits of bus i, $Q_{g,i,\max}$ and $Q_{g,i,\min}$ are reactive power limits of generator i, N_K and N_C are the number of transformers and compensators, $Q_{c,i}^t$, $Q_{c,i,\max}$, $Q_{c,i,\min}$ and $Q_{c,i,step}$ are the reactive power compensation, its limits and step size of compensator i at interval t, K_i^t, $K_{i,\max}$, $K_{i,\min}$ and $K_{i,step}$ are the ratio, its limits and step size of transformer i at interval t, $\mathbf{x}^t$ is the vector of control variables and state variables at interval t, N_{area} is the number of areas, $N_{G,k}$ is the number of generators in area k, $Q_{rs,k,\min}^t$ is the required DRPR for area k at interval t, $S_{k,i,\Delta}$, $S_{Qc,i,\Delta}$, $S_{k,i,\max}$ and $S_{Qc,i,\max}$ are maximum allowable action range between successive intervals and maximum allowable action number in a day of transformer i and compensator i respectively.

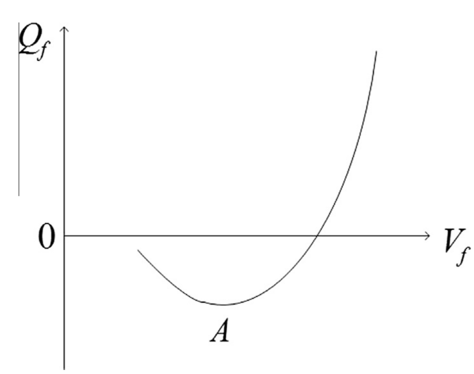

Fig. 1. *VQ* curve.