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Voltage instability performance of risk-based security constrained optimal power flow

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ABSTRACT

This paper uses *QV* curve analysis to investigate the voltage instability performance of risk-based security-constrained optimal power flow (RB-SCOPF), where risk is modeled to capture the system's overall security level. The RB-SCOPF is an improvement of the traditional security-constrained optimal power flow (SCOPF) model. In previous works, we have demonstrated that the operating conditions obtained from RB-SCOPF were more secure (less risky) than those obtained from SCOPF. This raises the question of whether the RB-SCOPF operating condition is more stable than the SCOPF-operating condition for a power system. We respond to this question by comparing the voltage stability performance of operating conditions obtained from RB-SCOPF and SCOPF. We employ a practical algorithm to obtain the *QV* curves at the buses of concern and calculate the reactive power reserves associated with each bus for operating conditions obtained from RB-SCOPF and SCOPF, respectively. Test results for IEEE 30-bus system are presented to illustrate that RB-SCOPF has better voltage instability performance than SCOPF.

1. Introduction

The risk-based security-constrained optimal power flow (RB-SCOPF) [1–4] extends the widely used SCOPF model [5–7] in an effort to enhance both security and economy of bulk power systems. The RB-SCOPF enforces three types of flow-related constraints: normal state deterministic flow limits, contingency state deterministic flow limits (the "N-1" criteria), and contingency state system risk which depends only on contingency states but not the normal state. Each constraint group is scaled by a single parameter allowing tradeoffs between deterministic constraints and system risk [8]. In previous works, we have demonstrated the long-term benefits of RB-SCOPF to the power systems in terms of both economy and security [9]. This raises the question of whether the RB-SCOPF operating condition is more stable than the SCOPF operating condition for other system problems. In this paper, we compare the voltage stability performance of operating conditions obtained from RB-SCOPF and SCOPF, respectively, using a steady-state voltage instability index, i.e., the reactive power margin at a given set of buses of a power system. The reactive power margin is obtained by calculating the difference between the 'nose point' of a *QV* curve and the reactive power corresponding to the base-case operating condition. It is aimed at assessing the system robustness with respect to voltage collapse [10].

In our previous work [1–4], risk is a probabilistic index designed to reflect the overall stress of the system's operating condition. It extends from the notion of risk as an expected severity, i.e., the summation over possible contingency states of each state's probability multiplied by its severity. The system's overall risk can be expressed as:

$$Risk(\underline{g}_1(\underline{P}_0), \ldots, \underline{g}_{NC}(\underline{P}_0)) = \sum_{k=1}^{NC} (Pr_k Sev(\underline{g}_k(\underline{P}_0))) \quad (1)$$

where NC is the number of contingencies. Pr_k and $Sev(\bullet)$ are occurrence probability and severity function for the kth contingency, respectively. $\underline{P}_0$ is the bus real power injection vector in the normal state, and $\underline{g}_k(\underline{P}_0)$ is the circuit power flow vector under the kth contingency. The overload severity of a post-contingency circuit is proportional to the circuit's power flow as a percentage of the circuit's emergency rating (PR): the higher the $\overline{PR}$ is, the more severe the loading condition is, as shown in Fig. 1. In the ISO New England system, three emergency ratings are defined [11]: (1) long time emergency (LTE) rating, which is intended to fit a daily load cycle for 4 h in winter and 12 h in summer; (2) short time emergency (STE) rating, which is a 15-min rating, i.e., a facility can operate at this rate for 15 min without suffering thermal damage; and (3) drastic

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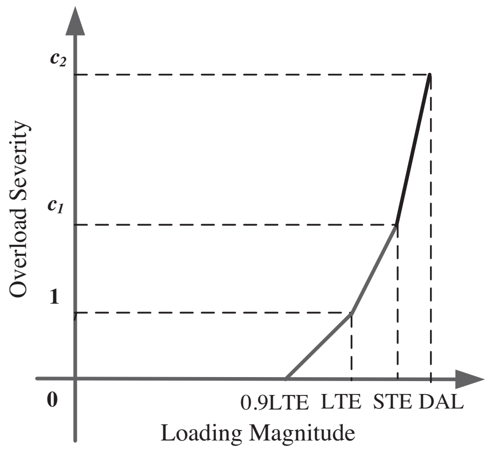

Fig. 1. Overload severity function.

action limit (DAL), which, if exceeded, requires immediate action. The severity function illustrated Fig. 1 is developed based on these emergency ratings. The severity value is set to 1 when the post-contingency flow is LTE. Parameters c_1 and c_2 are the corresponding severity values when the post-contingency flow is STE and DAL, respectively; they should be chosen to ensure the convexity of the function.

The compact form of SCOPF can be formulated as follows:

$$\text{Min} \quad \{f(\underline{P}_0)\} \tag{2}$$

$$s.t. \quad \underline{h}(\underline{P}_0) = \underline{0} \tag{3}$$

$$\underline{g}_{\min} \le \underline{g}(\underline{P}_0) \le \underline{g}_{\max} \tag{4}$$

$$\underline{g}'_{\min} \le \underline{g}_k(\underline{P}_0) \le \underline{g}'_{\max}, \quad k = 1, \ldots, NC \tag{5}$$

where $\underline{P}_0$ are the real power injections at each node. Index k denotes system state, while $k = 0$ represents the normal condition, and $k > 0$ represents post-contingency conditions. Eq. (2) optimizes an economic function $f(\underline{P}_0)$ (e.g., supply offers less demand bids), Eq. (3) are the pre-contingency power flow equations, (4) are line loading constraints under normal (no contingency) conditions, and (5) are line loading constraints under each of NC contingencies. Under this preventive control model, the real power injections $\underline{P}_0$ do not change.

The RB-SCOPF model introduces a constraint on system's risk requirement. It can be formulated as:

$$\text{Min} \{f(\underline{P}_0)\} \tag{6}$$

$$s.t. \quad \underline{h}(\underline{P}_0) = \underline{0} \tag{7}$$

$$\underline{g}_{\min} \le \underline{g}(\underline{P}_0) \le \underline{g}_{\max} \tag{8}$$

$$K_C \underline{g}'_{\min} \le \underline{g}_k(P_0) \le K_C \underline{g}'_{\max}, \quad k = 1, \ldots, NC \tag{9}$$

$$0 \le Risk(\underline{g}_1(\underline{P}_0), \ldots, \underline{g}_{NC}(\underline{P}_0)) \le K_R Risk_{\max} \tag{10}$$

where Pr_k is the probability of occurrence for the kth state. $Risk_{\max}$ is limit of the system's security level. Constraint (10) restrains the system's overall risk level. Parameters K_C and K_R are coordination factors used to scale the constraint limits. The choice of K_C and K_R enables one to impose control over two kinds of tradeoffs: (1) between security and economics, in that the higher K_C and K_R are, the more economic and less secure the system is; and (2) between system risk and individual circuit overload, in that increasing K_C decreases individual circuit security (by allowing increased post-contingency flows) while increasing K_R decreases system security. Ref. [1] proposed three different operational modes for RB-SCOPF: highly secure mode (HSM), economic-secure mode (ESM), and highly economic mode (HEM), where K_C was chosen as 1, 1.05 and 1.20, respectively. Only ESM and HEM modes allow post-contingent overflows; no overflow is permitted in the normal state.

The rest of this paper is organized as follows. In Section 2, the computational strategy to solve RB-SCOPF is proposed. In Section 3, the general voltage instability analysis method based on QV curves is described. Section 4 presents the simulation results on the IEEE 30-bus system. Section 5 discusses the reason why RB-SCOPF has better voltage instability performance over SCOPF. Finally, Section 6 presents final remarks.

2. The computational strategy of RB-SCOPF

The SCOPF is a special form of RB-SCOPF when $K_C = 1$ and $K_R = +\infty$ in Eqs. (6)–(10). A two-layer decomposition strategy is proposed to solve RB-SCOPF: in the external layer, the master problem is a SCOPF problem. The SCOPF result is then sent to a risk-checking subproblem. If the system's risk requirement is not satisfied, a risk constraint is generated and sent back to the master SCOPF problem; in the internal layer, a modified SCOPF problem is solved. It includes all the constraints in a traditional SCOPF problem (as shown in (7)–(9)), as well as the risk constraints from the external subproblem. The computational strategy is shown in Fig. 2.

A SCOPF problem with AC power flow constraints can generally be solved in two ways: (1) using interior-point method or some other heuristic methods, e.g., genetic algorithm and particle swarm optimization [12,13], to solve the AC OPF model directly. Historically, the AC OPF models have not been used in electricity markets, in part because of the current software's limitations on handling the nonlinear constraints effectively. (2) Iterating between a linearized based case OPF problem and AC power flow contingency analysis. The procedure is shown in the internal layer of Fig. 2. The base case is a DC OPF problem. The real power calculated from the base case are provided as inputs to an AC power flow model, which attempts to check if there exist violations given the restrictions on voltage and reactive power generation limits. The second approach has been dominated in most ISOs/RTOs in the US [14].

In the RB-SCOPF problem, there are two kinds of risk constraints: one is the constraint related to single circuits, as shown in (A8)–(A11); and the other is the constraint related to the whole system, as shown in (A12). Assume that $\mathbf{x}$ represents the state and control variables in a SCOPF problem, and $\mathbf{y}$ represents variables related to risk, we can write the RB-SCOPF problem (6)–(10) into the following standard Benders decomposition form [15]:

$$\text{Min} \quad \boldsymbol{c}^T \mathbf{x} \tag{11}$$

$$s.t \quad Ax \ge b \tag{12}$$

$$\boldsymbol{Ex} + \boldsymbol{Fy} \ge \boldsymbol{h} \tag{13}$$

where (11) represents Eqs. (7)–(9), and (13) represents Eqs. (A8)–(A12). Matrixes $\boldsymbol{A}$, $\boldsymbol{E}$, and $\boldsymbol{F}$ represent the corresponding parameters in those equations. Vectors $\boldsymbol{b}$ and $\boldsymbol{h}$ represent the constants on the right side of the equations.

The master problem of Benders decomposition is:

$$\{Min \quad c^T x : Ax \ge b\} \tag{14}$$

Assume $\mathbf{x}^*$ is the optimal solution to (14). The corresponding subproblem associated with the master problem is

$$\{\text{Min} \quad 0 : \boldsymbol{F} \quad \boldsymbol{y} \ge \boldsymbol{h} - E \quad \mathbf{x}^*\} \tag{15}$$

The objective function is 0 because the cost function (6) in the original RB-SCOPF problem is related to the state and control variable $\mathbf{x}$, but not the risk variable $\mathbf{y}$.

To apply the Benders decomposition approach, first we need to ascertain if the subproblem (15) is feasible or not. However, the sizes of matrix $\boldsymbol{F}$ and vector $\mathbf{y}$ in subproblem (15) are large when a