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Calculation of optimal load margin based on improved continuation power flow model

Xiaoming Dong, Chengfu Wang *, Zhihao Yun, Xueshan Han, Jun Liang, Yiming Wang, Penghui Zhao

Key Laboratory of Power System Intelligent Dispatch and Control of the Ministry of Education, Shandong University, Jinan 250014, China

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ABSTRACT

This study proposed an improved continuation power flow (CPF) model to calculate the *load margin* for voltage stability. A self-adjusting step-size controlling scheme of CPF, which is based on the iterations in the corrector and the reactive power reserve of generator buses, is presented. The load margin here is defined either by encountering the saddle node bifurcation (SNB) or the limit-induced bifurcation (LIB). To confirm the LIB, a rapid approach is proposed to calculate the sensitivity of voltage magnitude to reactive power injection change for load buses. Because CPF with distributed slack bus (DSB) could generate different load margin results corresponding to various allocations of imbalanced power, optimization techniques should be adopted in the search for maximizing the load margin. Therefore, the improved CPF is integrated with an evolutionary mechanism-based particle swarm optimization (PSO) method via coordinate transformation. Furthermore, parallel processing is deployed in the programming for high-performance computing. The case studies for the IEEE 5-bus and IEEE 14-bus test systems demonstrate the efficiency of the proposed approaches.

1. Introduction

A significant task for power system analysis computations [1] is estimating the maximum power that can be safely transferred from the source to the load. All types of power transfer limits, such as system security, reliability and stability, should be considered while discussing related issues. The rampant increase in voltage instability incidents emphasizes the need to examine voltage stability [2,3]. Static voltage stability approaches, regardless of the complexity and variety of the dynamic behavior of the facilities in power systems [4–6], still present some particular advantages [7]. Voltage collapses are always accompanied by a heavy load; therefore, the maximum loading point [8], or alternatively the load margin [9], is regarded as an efficient evaluation for the static voltage stability of power systems [10]. To evaluate the load margin, load flow formulations are used to calculate the increase in the electric generation and power load from the base state to a critical state [11]. However, the conventional load flow encounters numerical ill-conditioning problems [12] as the system state approaches saddle node bifurcation (SNB). Therefore, the continuation power flow (CPF) [13–18] is presented to solve the parameterized load flow formulations [19] with alternating predictor and corrector steps and is expected to produce the load margins of the SNB and limit-induced bifurcation (LIB) [18] with good convergence. Furthermore, the CPF models that are suitable for distribution systems are proposed in [19,20]. Due to the continuous improving in stepsize control [21,22] and parameterization technique [23], the CPF model are able to be used in system analysis with correspondingly good performance.

In traditional load flow formulations, the system power imbalance between the given power demand and generation is handled by one sole slack bus [21] rendering the fixed voltage magnitude and voltage phase angle. For practical power system operation, the imbalanced power that result in change of system frequency is actually supplied by multiple distributed buses. Thus, one can expect that errors, which could be significant for certain classes of systems, have been introduced. Therefore, treatments of DSB are introduced in load flow problems [24,25]. Furthermore, the CPF model is improved by involving the formulations of DSB [26]. However, vary load margins could be generated due to different allocation of imbalanced power corresponding to certain deployment of DSB. Then, an open question is to identify the most extreme case of imbalanced power allocation for system operation. Thus, the major concerns of this study includes revealing the potential magnitude of such load margin errors, and meanwhile exploring high-performance approach to calculate the optimal load margin considering DSB.

* Corresponding author at: Room 503, School of Electrical Engineering, Qian-FoShan Campus, Shandong University, Jinan 250014, China.

E-mail addresses: dongxiaoming@sdu.edu.cn (X. Dong), wangcf@sdu.edu.cn (C. Wang).

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This study presents an improved CPF model that incorporates DSB to allocate the imbalanced power. Because the type of "loss of voltage control" voltage instability is presented in [27], it is defined in this study as a special case of LIB characterized by the exhaustion of all of the reactive power supporting the system. An auto-adaptive step-size controlling method based on the iterations of the CPF corrector and the generator reactive power reserve is presented. The CPF predictor–corrector step size can be increased moderately to speed up computation and decreased while get close to the critical state (SNB or LIB) for accuracy. Based on the algorithms in bifurcation recognition [28–30], the VQ sensitivity analysis method [31] is introduced to capture LIB point. An alternative scheme is adopted to avoid massive calculation to obtain the inverse of Jacobin matrix. As a result, the load margins corresponding to various schemes of imbalanced power allocation and bifurcation modes can be obtained using an efficient and precise CPF model. Due to the complexity of load margin profile constrained either by SNB or LIB, the relationship between imbalanced power allocation and load margin cannot be clarified with an analytical expression. Thus, a hybrid optimization approach that involves the improved CPF and an evolutionary mechanism-based particle swarm optimization (PSO) algorithm is presented to obtain the optimal load margins. Because the unacceptable performance of PSO in solving constrained optimization problems, a coordinate transformation-based method is deployed in the hybrid approach to convert the problem into unconstrained one. Furthermore, parallel processing technology is used in the programming of the hybrid approach to make the best use of the computer resources in hand.

The remainder of this paper is organized as follows. Section 2 describes the DSB based load flow model. The formulations and procedures of the improved CPF considering DSB are derived in Section 3. The description of the hybrid optimization approach based on the improved CPF and PSO is given in Section 4. Next, Section 5 presents case studies to illustrate the performance of the presented approaches. Finally, the main results are summarized and the key conclusions are drawn in Section 6.

2. Load flow model with DSB

First, the conventional load flow equations with a sole slack bus can be expressed as shown in (1); the equations consist of the reactive power balance equations for PQ buses and the active power balance equations for PV and PQ buses. The total number of the network buses is set to N, among which the number of PV buses is m. Thus, 2N-m-2 equations should be involved in (1).

$$\begin{cases} \mathrm{f}_i = P_i^G - P_i^L - \mathrm{p}_i(\mathbf{V},\boldsymbol{\theta}) = P_i - \mathrm{p}_i = 0 \quad (i = 1, 2, \cdots, N-1) \\ \mathrm{f}_{i+N-1} = Q_i^G - Q_i^L - \mathrm{q}_i(\mathbf{V},\boldsymbol{\theta}) = Q_i - \mathrm{q}_i = 0 \quad (i = 1, 2, \cdots, N-m-1) \end{cases} \tag{1}$$

with

$$\begin{cases} \mathbf{V} = [\,V_1 \quad V_2 \quad \cdots \quad V_{N-m-1}\,] \\ \boldsymbol{\theta} = [\,\theta_1 \quad \theta_2 \quad \cdots \quad \theta_{N-1}\,] \end{cases} \tag{2}$$

where P_i^G and P_i^L represent the active power generation and demand, respectively, at bus i; Q_i^G and Q_i^L represent the reactive power generation and demand, respectively, at bus i; P_i is the active power injected into the network at bus i; Q_i is the reactive power injected at bus i; the function f represents the active or reactive power balance equation; the vector $\mathbf{V}$ presented by (2) indicates the voltage magnitudes at PQ buses; and the N-1-dimensional vector $\boldsymbol{\theta}$ represents the voltage phase angles at the PV and PQ buses. Detailed expressions of functions $\mathrm{p}_i(\cdot)$ and $\mathrm{q}_i(\cdot)$ are given as follows:

$$\begin{cases} \mathrm{p}_i = \sum_{j\in i}^{N} V_i V_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) \\ \mathrm{q}_i = \sum_{j\in i}^{N} V_i V_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) \end{cases} \tag{3}$$

where θ_{ij} is the phase angle between complex bus voltages V_i and V_j; G_{ii} and B_{ii} are the self-conductance and self-susceptance, respectively, at bus i; and G_{ij} and B_{ij} are the mutual conductance and mutual susceptance, respectively, between buses i and j. Next, a set of additional parameters that are expressed as $\mathbf{A}$ in (4) are introduced to indicate the imbalanced power allocation coefficients.

$$\mathbf{A} = [\,\alpha_1 \quad \alpha_2 \quad \cdots \quad \alpha_N\,]^T \quad \left(\sum_{i=1}^{N}\alpha_i = 1; \quad 1 \geqslant \alpha_i \geqslant 0\right) \tag{4}$$

Once the parameters in $\mathbf{A}$ are given by the imbalanced power allocation coefficients, they are fixed throughout load flow and CPF calculating process. Furthermore, the sum of those parameters is equal to 1. Thus, we obtained the relationship given in (5), where the parameter μ is introduced to indicate the level of the imbalanced power.

$$\mu = \sum_{i=1}^{N} \mu\alpha_i \tag{5}$$

Next, the improved load flow formulations can be expressed as (6).

$$\begin{cases} \mathrm{f}_i = P_i + \mu\alpha_i - \mathrm{p}_i = 0 \quad (i = 1, 2, \cdots, N) \\ \mathrm{f}_{i+N} = Q_i - q_i = 0 \quad (i = 1, 2, \cdots, N-m) \end{cases} \tag{6}$$

In particular, f_N represents the active power balance equation of the conventional slack bus that is ignored in conventional load flow formulations. Thus, the compact form of (7) is as follows:

$$\begin{aligned} &\mathbf{f}(\mathbf{X}) = 0 \\ &(\mathbf{X} = [\mathbf{V} \quad \boldsymbol{\theta} \quad \mu] = [\,x_1 \quad x_2 \quad \cdots \quad x_{2N-m}\,]) \end{aligned} \tag{7}$$

where vector $\mathbf{X}$ represents all of the unknowns. To solve (7), the Newton iterative formats are established, as shown in (8).

$$\begin{cases} \mathbf{f}(\mathbf{X}^{(k)}) = \mathbf{J}_{PF}^{(k)}(\Delta\mathbf{X}^{(k)})^T \\ \mathbf{X}^{(k+1)} = \mathbf{X}^{(k)} + \Delta\mathbf{X}^{(k)} \end{cases} \tag{8}$$

with

$$\mathbf{J}_{PF}^{(k)} = \left(\left. \frac{\partial \mathbf{f}(\mathbf{X})}{\partial \mathbf{X}} \right|_{\mathbf{X}=\mathbf{X}^{(k)}} \right) \tag{9}$$

where (k) and $(k+1)$ represent the count of the iteration step and the matrix $\mathbf{J}_{PF}$ represents the Jacobin matrix of (7). For Newton iterative calculation, the unknown variables could be initialized for a "flat start" as follows:

$$\mathbf{X}^{(0)} \Rightarrow \begin{cases} \mathbf{V}^{(0)} = [\,1 \quad 1 \quad \cdots \quad 1\,] \\ \boldsymbol{\theta}^{(0)} = [\,0 \quad 0 \quad \cdots \quad 0\,] \\ \mu^{(0)} = 0 \end{cases} \tag{10}$$

The following relationship could be used to confirm the convergence of (21):

$$\|\mathbf{f}(\mathbf{X}(k_c))\|_\infty \leqslant \varepsilon \tag{11}$$

where ε is a small positive number that is given in advance; k_c represents the step count at which the iteration process converges.