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The interval sensitivity analysis and optimization of the distribution network parameters considering the load uncertainty

Zhigang Lu [a,*], Jia Liu [a,b], Yane Liu [a,c], Rongrong Ding [a], Fang Yang [a]

[a] Key Lab of Power Electronics for Energy Conservation and Motor Drive, Yanshan University, Hebei Province 066004, PR China
[b] Qinhuangdao Power Corporation Limited, Qinhuangdao 066004, Hebei Province, PR China
[c] State Grid Jibei Changli Power Supply Co. Ltd., Changli Hebei 066600, PR China

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ABSTRACT

This paper proposes an advanced approach to optimize the line and transformer parameters for the distribution system. The approach first adopts a novel set of interval sensitivity models, based on which an interval forward–backward power flow algorithm and an interval analysis method are further developed. In order to improve computational speed, this approach uses a simplified set models to calculate power system loss interval sensitivity with respect to the admittance of lines and transformers. An interval objective function is formulated and the optimization problem is solved with a discrete bacterial colony chemotaxis algorithm. The applicability and effectiveness of the proposed approach is demonstrated on two real distribution systems.

Introduction

In recent years, with the considerable increase of the load demand, some distribution lines and transformers can no longer meet the actual power delivery requirements, which leads to the loss increase and distribution system operation. Hence, the identification of lines and transformers that are responsible for the system loss increase becomes necessary in order to establish the reconstruction strategies.

The subject of power system loss sensitivity is widely addressed in various areas such as transaction evaluation, voltage stability, sensitivity analysis and loss minimization [1–6]. Refs. [7–9] present a set of models to calculate power system loss sensitivities with respect to power system parameters. These models are derived from the Tellegen's theorem and the adjoint network concept.

Ref. [10] adopts the least-square fitting technique to fit the relationship curves between the line cross-sectional area and investment, proposes a sensitivity analysis method to optimize line parameters based on Particle Swarm Algorithm, and formulates the objective function to minimize the comprehensive investment cost and system power loss. Ref. [11] uses the economic current density and load rate to reconstruct lines and transformers and analyze their economic operation range. Based on the definition of the conjugate branch current sensitivity with respect to the line or transformer parameters, the power system loss sensitivity with respect to the line or transformer parameters is calculated. According to the loss sensitivities, it is possible to determine every component's influence degree to the power system loss, and provide an easy way for estimating the network loss when the parameters are changed. Besides, Ref. [12] selects optimization interval using the lines and transformers economic operation range. In addition, a particle location library is establish to update particle location. Ref. [13] improves the adequacy of constructed sensitivity models and allows to consider a power system reaction on the basis of constructing so-called functionally oriented equivalents.

Taking load uncertainties [14] into consideration, the loss sensitivity with respect to certain parameters varies along with time changes. Therefore, this paper focuses on computing the loss interval sensitivities over a period of time. The meaning of the loss interval sensitivity is that the value of the sensitivity is an interval number consisting of all the numbers between a pair of given numbers. The two given numbers are referred to as upper and lower limits. Using the loss interval sensitivities makes it more reasonable to identify weakness in the distribution system and establish reconstruction measures in time.

This paper applies the three-phase system modeling technique [15] including nine transformer connection types (both grounded and ungrounded connections), lines, switches, and ZIP loads. In

* Corresponding author. Address: School of Electrical Engineering, Yanshan University, Qinhuangdao, Hebei 066004, PR China.

E-mail addresses: zhglu@ysu.edu.cn (Z. Lu), ljia1987@sina.com (J. Liu), lyeysu@163.com (Y. Liu), 1250094720@qq.com (R. Ding), faayaa2013@hotmail.com (F. Yang).

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Table 1
Interval sensitivities for lines.

Line no.	Interval sensitivity	
	Lower limit	Upper limit
L1	1.06E-5	1.89E-5
L2	1.72E-7	5.88E-7
L3	1.18E-7	3.27E-7
L4	2.65E-8	6.11E-8
L5	1.35E-8	5.05E-8
L6	7.64E-8	1.60E-7
L7	5.33E-9	9.71E-9
L8	2.48E-9	5.68E-9
L9	2.44E-8	5.14E-8
L10	9.37E-10	2.79E-9

Table 2
Interval sensitivities for transformers.

Transformer no.	Interval sensitivity	
	Lower limit	Upper limit
T1	1.48E-4	2.78E-4
T3	1.71E-4	3.28E-4
T4	3.40E-4	4.89E-4
T5	1.28E-4	2.04E-4
T6	1.43E-4	1.63E-4
T7	2.55E-4	6.06E-4
T8	1.86E-4	3.41E-4
T9	9.50E-5	1.40E-4
T10	4.17E-5	7.15E-5

order to deal with the load uncertainty problems, this paper proposes an interval computation-based forward–backward power flow algorithm [16] for distribution systems and an interval analysis method to optimize parameters of the lines and transformers.

Interval sensitivity models

According to the power system loss sensitivity with respect to power system parameters, we can find out some lines and transformers which have a greater impact on the power system losses than the others. However considerable computation time is required because of the large dimension of the matrix [10,11] when the distribution system has large scale. This paper presents a new set of models for computing sensitivity of power system losses with respect to the admittance. These new models can save computation time significantly.

Voltage and current interval sensitivities model

Considering a network with the node number N_0, the network node voltage equation can be described as:

Table 4
Interval sensitivities for lines.

Line no.	Interval sensitivity	
	Lower limit	Upper limit
L1	2.24E-10	4.12E-10
L2	5.14E-7	1.36E-6
L3	6.01E-7	1.39E-6
L4	6.95E-7	1.65E-6
L5	1.00E-10	1.00E-10
L6	1.15E-7	2.62E-7
L7	2.81E-8	8.81E-8
L8	5.55E-8	1.08E-7
L9	5.41E-8	1.05E-7
L10	5.55E-8	9.25E-8
L11	3.96E-7	6.39E-7
L12	1.91E-8	3.26E-8
L13	5.16E-8	7.88E-8
L14	8.06E-10	1.30E-9
L15	1.60E-9	2.20E-9

$$\boldsymbol{A}\boldsymbol{Y}_b\boldsymbol{A}^T\boldsymbol{V}_n = \boldsymbol{A}(\boldsymbol{i}_g - \boldsymbol{Y}_b\boldsymbol{V}_g) \tag{1}$$

where $\boldsymbol{V}_n$ is the vector of the node voltage; the vector $\boldsymbol{i}_g$ is the equivalent injection current in the equivalent model of generators; the vector $\boldsymbol{V}_g$ is the equivalent voltage in the equivalent model of loads; $\boldsymbol{A}$ is the incidence matrix of the network; $\boldsymbol{Y}_b$ is the matrix of the branch parameters; $\boldsymbol{A}\boldsymbol{Y}_b\boldsymbol{A}^T = \boldsymbol{Y}_n$ is the nodal admittance matrix; (1) can be simplified as:

$$\boldsymbol{Y}_n\boldsymbol{V}_n = \boldsymbol{A}(\boldsymbol{i}_g - \boldsymbol{Y}_b\boldsymbol{V}_g) \tag{2}$$

According to (2), the change in the node voltage $\Delta\boldsymbol{V}_n$ is:

$$\Delta\boldsymbol{V}_n = -\boldsymbol{Y}_n^{-1}\boldsymbol{A}\Delta\boldsymbol{Y}_b(\boldsymbol{V}_g + \boldsymbol{V}_b) \tag{3}$$

The equation of the branch voltage and current can be written as:

$$\begin{cases} \boldsymbol{V}_b = \boldsymbol{A}^T\boldsymbol{V}_n \\ \boldsymbol{I}_b = (\boldsymbol{V}_b + \boldsymbol{V}_g)\boldsymbol{Y}_b \end{cases} \tag{4}$$

Based on the interval analysis, by using (3) and (4), the branch voltage interval sensitivities and the branch current interval sensitivities with respect to the admittance can be calculated from the following equations:

$$\begin{cases} \widehat{M}_{ni} = -(\boldsymbol{A}\boldsymbol{Y}_b\boldsymbol{A}^T)^{-1}\boldsymbol{A}\frac{\mathrm{d}\boldsymbol{Y}_b}{\mathrm{d}y_i}(\widehat{\boldsymbol{V}}_g + \widehat{\boldsymbol{V}}_b) \\ \widehat{M}_{bi} = -\boldsymbol{A}^T(\boldsymbol{A}\boldsymbol{Y}_b\boldsymbol{A}^T)^{-1}\boldsymbol{A}\frac{\mathrm{d}\boldsymbol{Y}_b}{\mathrm{d}y_i}(\widehat{\boldsymbol{V}}_g + \widehat{\boldsymbol{V}}_b) \\ \widehat{M}^*_{bi} = -\boldsymbol{A}^T((\boldsymbol{A}\boldsymbol{Y}_b\boldsymbol{A}^T)^{-1})^*\boldsymbol{A}\frac{\mathrm{d}\boldsymbol{Y}_b}{\mathrm{d}y_i} \times (\widehat{\boldsymbol{V}}_g + \widehat{\boldsymbol{V}}_b)^* \end{cases} \tag{5}$$

$$\begin{cases} \widehat{N}_{bi} = \frac{\mathrm{d}\boldsymbol{Y}_b}{\mathrm{d}y_i}(\widehat{\boldsymbol{V}}_g + \widehat{\boldsymbol{V}}_b) - \boldsymbol{Y}_b\boldsymbol{A}^T(\boldsymbol{A}\boldsymbol{Y}_b\boldsymbol{A}^T)^{-1} \times \boldsymbol{A}\frac{\mathrm{d}\boldsymbol{Y}_b}{\mathrm{d}y_i}(\widehat{\boldsymbol{V}}_g + \widehat{\boldsymbol{V}}_b) \\ \widehat{N}^*_{bi} = \frac{\mathrm{d}\boldsymbol{Y}^*_b}{\mathrm{d}y_i}(\widehat{\boldsymbol{V}}_g + \widehat{\boldsymbol{V}}_b)^* - \boldsymbol{Y}^*_b\boldsymbol{A}^T \times ((\boldsymbol{A}\boldsymbol{Y}_b\boldsymbol{A}^T)^{-1})^*\boldsymbol{A}\frac{\mathrm{d}\boldsymbol{Y}^*_b}{\mathrm{d}y_i}(\widehat{\boldsymbol{V}}_g + \widehat{\boldsymbol{V}}_b)^* \end{cases} \tag{6}$$

Table 3
Optimization results for 12-bus radial distribution system.

Optimization results			
Sensitivity threshold	[0, 0.00085]	[0, 0.0008]	[0, 0.0005]
Initial loss (p.u.)	[0.0032, 0.0078]	[0.0032, 0.0078]	[0.0032, 0.0078]
Initial loss rate	[0.0223, 0.0342]	[0.0223, 0.0342]	[0.0223, 0.0342]
Cost savings/ten thousand yuan (h)	[−2.9886E-6, 0.1089E-5]	[−3.6312E-6, 1.2538E-5]	[−2.1632E-5, 7.1925E-4]
A change in loss (p.u.)	[−9.53E-5, −5.11E-5]	[−1.34E-4, −6.43E-5]	[−1.65E-4, −3.15E-5]
New loss rate	[0.0219, 0.0341]	[0.0216, 0.0340]	[0.0214, 0.0342]
T15 (initial model)	S7–80	S7–80	S7–80
T15 (new model)	S9–100	S9–100	S9–100
T7 (initial model)	S9–100	S9–100	S9–100
T7 (new model)	S9–125	S9–125	S9–125
T4 (initial model)	–	S9–100	S9–100
T4 (new model)	–	S9–125	S9–125
T8 (initial model)	–	–	S9–250
T8 (new model)	–	–	S9–315