The Journal of Engineering

The 14th IET International Conference on AC and DC Power Transmission (ACDC 2018)

Improved sensitivity analysis method and decision error discussion for limiting short-circuit current of power grid

eISSN 2051-3305
Received on 23rd August 2018
Accepted on 19th September 2018
E-First on 6th December 2018
doi: 10.1049/joe.2018.8522
www.ietdl.org

Shixiong Qi[1] ✉, Xiuli Wang[1], Shijun Tian[1], Ruogu Wang[2]
[1]*State Key Laboratory on Electrical Insulation and Power Equipment, Xian Jiaotong University, Xi'an, People's Republic of China*
[2]*State Grid Shaanxi Electric Power Research Institute, Xi'an, People's Republic of China*
✉ *E-mail: qishixiong@stu.xjtu.edu.cn*

Abstract: This study mainly focuses on the method of limiting short-circuit current of a power grid by partial transmission switching. The restrictive effect of short-circuit current and the integrality of the power grid should be considered before the choosing the transmission lines. By analysing the relationship between transmission switching and self-impedance of bus with increasing short-circuit current magnitude, a sensitivity matrix can be derived. Based on sensitivity analysis, a set of the least transmission switching is chosen, which can limit short-circuit current to the maximum. This study improves the method of transmission lines selection by sensitivity analysis. The improved sensitivity analysis method directly selects a set of transmission switching lines by the maximum value of weighted sensitivity coefficient instead of selecting lines one by one. It requires less calculation and has a high-computation speed, but there are engineering errors. This work also studies the error influencing the decision of lines selection in different power grid scales. The effectiveness of the improved sensitivity analysis method is verified by several case studies. The cases of different power system scales are utilised for discussing the impact of error on decision of lines selection and for drawing the scope of the improved sensitivity analysis method.

1 Introduction

With the continuous expansion of the power grids, the closer interconnection between power networks [1] and the increased number of generators [2] will lead to a larger short-circuit current (SCC) value [3]. The rising SCC has affected the security of power grids operation. There are mainly two strategies to limit the short-circuit current level of a power grid, which are transmission switching to change the grid structure [4] and power equipment upgrade [5]. Due to the economics of power grid planning, transmission switching is a widely used method. Transmission switching to change the grid structure appropriately reduces the electrical connection of the power network [6].

Optimal transmission switching (OTS) [7] has recently drawn much attention, which is a means of changing the topology of the power grid for control purposes by switching certain transmission lines or transformers during power grid operation [8]. The controllability of the power grid can be fully utilised by the OTS, so that the power grid can flexibly respond to various situations of the system operation [9], such as unit commitment operation, load fluctuation and power system faults. Therefore, OTS can improve system economics, security and self-healing capabilities, and these advantages are exactly what the modern smart grid requires [10]. OTS is modelled as a mixed integer programming (MIP) problem, in which the operating status of each line is represented by the discrete variable (0–1). For increasing the performance of OTS, many strategies have been proposed [11, 12].

Actually, transmission switching method mitigates the SCC by adding constraints about the SCC based on the OTS model [13]. However, in many power systems, the operators choose the switching lines to limit the SCC using trail and experience. This is an inefficient and imprecise method of finding a switching solution. An impedance-sensitivity-based method is introduced to find a desirable switching solution [14]. The optimisation theory takes into account the OTS with SCC limitation constraints [15].

In [15], a set of transmission lines can be calculated by the optimality of the solution. However, there are accumulated engineering errors in the solution. When one transmission line is switched off, the admittance matrix of the whole power grid is changed, so the next choice of transmission switching depends on the new admittance matrix. If a set of transmission switching depends on the admittance matrix of the original power grid, the mutual influence between the transmission lines is neglected. It led to errors in the calculation of the SCC.

This paper studies this problem further and improves the method of transmission switching selection by sensitivity analysis. It is worth emphasising whether the errors of the SCC (decision error) affect the decision of transmission switching or not. The set of lines selection method has simplified the solution process, requires less calculation and has high-computational speed. Single and multiple lines selection method avoids engineering errors and make accurate lines selection. The major advantages of this paper are as follows:

This paper focuses on studying the error of SCC influencing the decision of transmission switching selection in different power grid scales.

An improved sensitivity analysis method is proposed, which combines the advantages of the set of lines selection method and single and multiple lines selection method. In the premise of ensuring the correct decision of transmission switching selection, the most efficient method is chosen in different power grid scales.

2 Methodology

2.1 Adding branch method

The per-unit value of the SCC can be calculated by the impedance matrix. However, the admittance matrix of the power grid is easy to obtained, whereas the impedance matrix is obtained by inversion of the admittance matrix. It requires huge calculation especially in the case of a large-scale power grid, so the adding branch method is utilised for obtaining new impedance matrix when one line is switched off. The equivalent model of the adding branch method is shown in Fig. 1. Negative impedance of equal magnitude is added across the selected transmission line.

The impedance matrix and current vector of the original grid are $\boldsymbol{Z}_N$ and $\boldsymbol{I}$. After adding the negative impedance, $\boldsymbol{I}'$ is expressed as follows:

$$\boldsymbol{I}' = [\dot{I}_1\,\dot{I}_2 \cdots \dot{I}_i - \dot{I}_{ij} \cdots \dot{I}_j + \dot{I}_{ij} \cdots \dot{I}_m]^{\mathrm{T}} = \boldsymbol{I} - \boldsymbol{\alpha}\dot{I}_{ij} \quad (1)$$

where $\boldsymbol{\alpha}$ is a feature vector, the elements of the selected transmission line are 1 or −1 and the others are zero. The relationship between the original impedance matrix $\boldsymbol{Z}_N$ and new impedance matrix $\boldsymbol{Z}'_N$ is expressed as follows:

$$\mathbf{Z}_N = \mathbf{Z}_N - \frac{1}{Z_{\mathrm{LL}}}\mathbf{Z}_L\mathbf{Z}_L^{\mathrm{T}} \tag{2}$$

where $\mathbf{Z}_L = \boldsymbol{Z}_N\boldsymbol{\alpha}$ and $Z_{\mathrm{LL}} = \boldsymbol{\alpha}^{\mathrm{T}}\boldsymbol{Z}_N - z_{ij}$.

On this basis, the self-impedance of bus where the SCC exceeds the limits can be expressed as follows:

$$Z'_{ff} - Z_{ff} = -\frac{\left(Z_{fi} - Z_{fj}\right)^2}{Z_{\mathrm{LL}}} \tag{3}$$

$$Z_{\mathrm{LL}} = A_{\mathrm{M}}^{\mathrm{T}}\boldsymbol{Z}_N - z_{ij} = Z_{jj} + Z_{ii} - 2Z_{ij} - z_{ij} \tag{4}$$

where Z_{ff}, Z'_{ff}, and Z_{jj} and Z_{ii} are self-impedances of the SCC bus and buses of the selected transmission line, respectively. Z_{fi}, Z_{fj} and Z_{ij} are mutual impedances between buses. z_{ij} is the impedance of transmission switching. The new self-impedance of the SCC bus can be calculated by (3).

2.2 Sensitivity analysis of the SCC

Sensitivity analysis of the SCC studies the influence of the change of power grid structure on the SCC. Specifically, one transmission line is switched off, limiting the magnitude of SCC.

The per-unit value of the SCC of three-phase fault is calculated as

$$I_f^* = \frac{1}{Z_{ff}} \tag{5}$$

Based on the adding branch method, the sensitivity of the SCC can be computed as follows:

$$\Delta I_f^* = \frac{\left(Z_{fi} - Z_{fj}\right)^2}{\left(Z_{jj} + Z_{ii} - 2Z_{ij} - z_{ij}\right)Z_{ff}^2 - Z_{ff}\left(Z_{fi} - Z_{fj}\right)^2} \tag{6}$$

$$s_{kf} = \frac{\Delta I_f^* S_{\mathrm{B}}}{\sqrt{3}U_{\mathrm{B}}} \tag{7}$$

where ΔI_f^* is changed quantity of the per-unit value of the SCC of three-phase fault. S_{B} and U_{B} are the base values of power and voltage, respectively. $s_{kf}$is the sensitivity coefficient of the transmission line k impacting the SCC of all buses.

The sensitivity of all transmission lines can be analysed and the sensitivity matrix can be derived. Actually, there are many overstandard buses in the power grid. Therefore, the weighted sensitivity coefficient characterises the effect of transmission line k limiting the SCC of all buses with the increase of SCC, and it can be computed as follows:

$$s_k = \sum_{f \in \Gamma} s_{kf}\left(\frac{I_f^*}{I_{\mathrm{cb}}^*} - 1\right) \tag{8}$$

where Γ is a set of buses with increasing SCC. s_k is the weighted sensitivity coefficient of the transmission line k. I_{cb}^* is the per-unit value of the breaking current of circuit interrupter. The sensitivity analysis is transmission switching selection by finding a set of maximum values of the weighted sensitivity coefficient.

2.3 OTS with SCC limitation constraints

OTS with SCC limitation constraints is an effective method of transmission switching selection. In [7], the typical OTS is shown as follows:

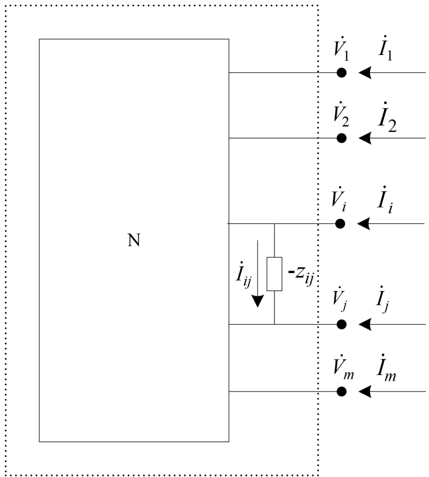

Fig. 1 *Equivalent model of transmission switching*

$$\min \quad \sum_g c_g P_g + \sum_k s_k \pi_k \tag{9}$$

$$\text{st} \quad B_k(\delta_i - \delta_j) - P_{ijk} + \pi_k \Omega_k \geq 0 \quad \forall k \tag{10}$$

$$B_k(\delta_i - \delta_j) - P_{ijk} - \pi_k \Omega_k \leq 0 \quad \forall k \tag{11}$$

$$\sum_{\forall k | j = n} P_{ijk} - \sum_{\forall k | i = n} P_{ijk} + \sum_{g \in n} P_g = PD_n \quad \forall n \tag{12}$$

$$\delta_n^{\min} \leq \delta_n \leq \delta_n^{\max} \quad \forall n \tag{13}$$

$$P_{ijk}^{\min}\pi_k \leq P_{ijk} \leq P_{ijk}^{\max}\pi_k \quad \forall k \tag{14}$$

$$P_g^{\min} \leq P_g \leq P_g^{\max} \quad \forall g \tag{15}$$

$$\sum_k (1 - \pi_k) \leq \Pi \tag{16}$$

Here, π_k is a state variable of transmission line k. $\pi_k = 1$ means that transmission line k is working, while $\pi_k = 0$ means that transmission line k is switched off. The objective function (9) minimises the total cost of generation and the least transmission switching. Moreover, (10) and (11) are the power flow constraints, where Ω_k is a large number that should be more than or equal to $B_k(\theta_i^{\max} - \theta_j^{\min})$. These two constraints are enforced to be strictly satisfied. Power balance at each bus is enforced by (12), and the voltage phase angle, power flow on transmission lines and generator outputs are enforced by (13)–(15), respectively. Π is the maximum number of transmission switching, and constraint (16) limits the number of transmission switching.

3 Solution strategy

In this section, two methods are compared and the improved sensitivity analysis method is proposed, which combines the advantages of the set of lines selection method and single and multiple lines selection method.

3.1 Method 1: the set of lines selection method

The set of lines selection method is a direct method of selecting a group of lines once. The characteristic of this method is that all transmission switching lines can be selected at a time by solving OTS. However, there are engineering errors in this computational process, because each transmission line affects the impedance matrix of the whole power grid. When one transmission line is switched off, the structure of power grid is changed, so the next selection of switching line depends on the new admittance matrix. If not, the interaction between the transmission lines is neglected. It leads to the errors in the calculation of the SCC.

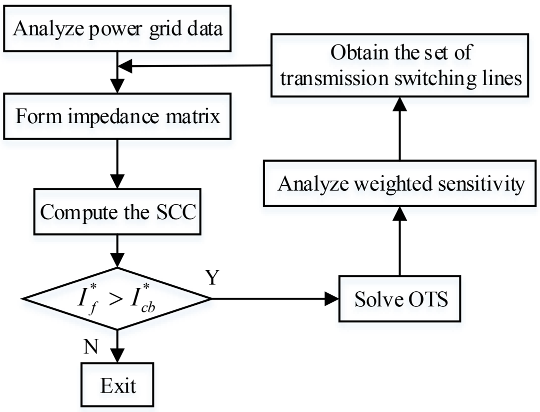

Fig. 2 *Framework for sensitivity analyses of Method 1*

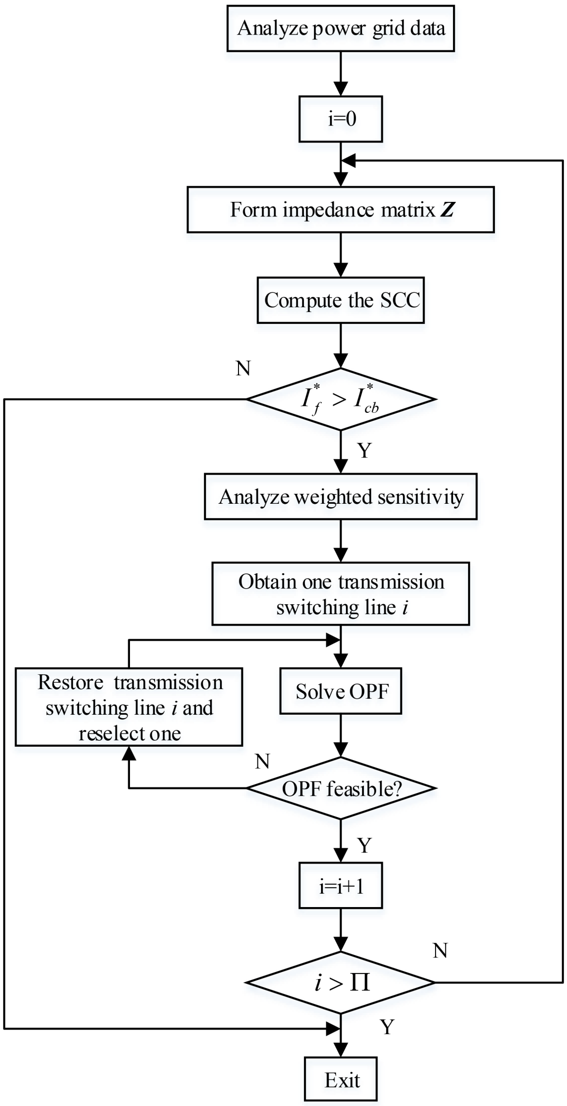

Fig. 3 *Framework for sensitivity analyses of Method 2*

The advantages of Method 1 are that it is a simplified solution process and requires less calculations. The framework of Method 1 is shown in Fig. 2.

3.2 Method 2: single and multiple lines selection method

The characteristics of this method are that only one transmission line is selected at a time. Then, the structure of the power grid is modified to reform the impedance matrix. Finally, the next transmission line is chosen by analysing the new network.

The advantages of Method 2 include avoiding engineering error and selecting accurate lines. However, this method needs to solve the optimal power flow many times for selecting transmission lines, so it requires a larger amount of calculation. The framework of Method 2 is shown in Fig. 3.

3.3 Decision error discussion between two methods

The proposed method in [15] is similar to Method 1. Actually, Method 1 cannot make optimal decision of transmission switching lines in different power grid scales. This problem is caused by accumulated engineering error. The paper focuses on the error of SCC in different power grid scales, and then, whether this error affects the decision of transmission switching or not; hence, it is called a decision error in this paper. On this basis, a selection is made to identify which method is suitable for a large-scale grid and which method is suitable for a small-scale grid by several cases.

4 Cases studies

In this section, the IEEE 14-bus system and IEEE 57-bus system as cases of this paper represent small-scale systems and large-scale systems, respectively. By solving two cases, the decision error will be discussed and the suitable method will be chosen in different situations. Then, in order to demonstrate the practical application of this method, the SCC limitation of Northwest China Power Grid will be solved.

4.1 Limitation of SCC in the IEEE 14-bus system

To illustrate the problem easily, this paper modifies the IEEE 14-bus system, as shown in Fig. 4.

In this paper, the parameters of the IEEE 14-bus system are shown as follows: $S_B = 100$ MVA, $U_B = 220$ kV and the maximal breaking current of circuit interrupter is 14 kA, and the per-unit value of sub-transient reactance (X_d'') of generators converts to system and is presented in Table 1.

First, some important weighted sensitivity coefficients of the transmission line in the two methods are presented in Table 2. The s_k indicates the integrated limitation effect of the line k on SCC. Hence, if s_k differs between the two methods, the transmission switching decision will commit mistakes.

As shown in Table 2, in Method 1, the bold values show weighted sensitivity coefficients, which are calculated from the original grid, so the second transmission switching is line 6. However, in Method 2, after the first transmission switching, weighted sensitivity coefficients are recalculated from the corrective grid, so the second transmission switching is line 3. This is a deviation of the decision caused by the accumulated error.

Second, the SCC limitation effectiveness of the two methods is different from each other, as shown in Fig. 5.

As shown in Fig. 5, there are two buses with overstandard SCC in the IEEE 14-bus system, which are bus 2 and bus 3 (red callout). Moreover, the decision of Method 1 is that line 1 and line 3 are switched off, while the decision of Method 2 is that line 1 and line

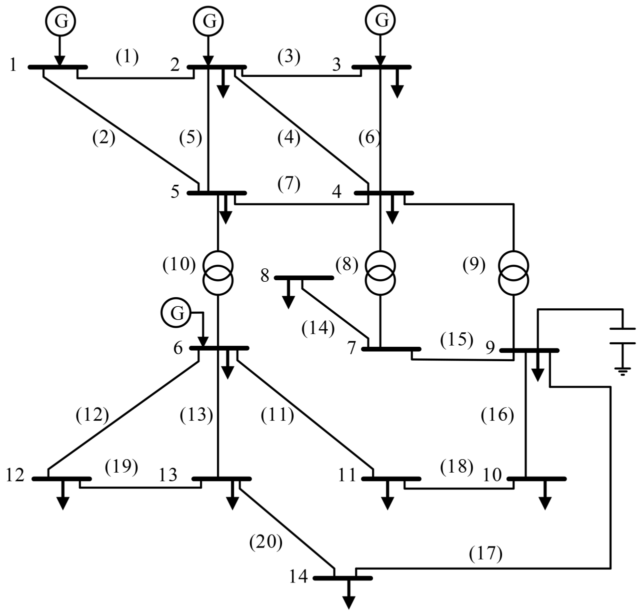

Fig. 4 *Diagram of the IEEE 14-bus system*

Table 1 Sub-transient reactance (X_d'') of generators of the IEEE 14-bus system

Generators	Gen. 1	Gen. 2	Gen. 3	Gen. 6
X_d''	0.0281	0.0297	0.0206	0.0206

Table 2 Weighted sensitivity coefficients of the IEEE 14-bus system

Branch	Method 1	Method 2-I	Method 2-II
1	**0.0405**	**0.0405**	0
2	0.0015	0.0015	0.0452
3	0.0249	0.0249	**0.065**
4	0.0099	0.0099	0.0512
5	0.0083	0.0083	0.0503
6	**0.025**	0.025	0.0643
7	0.0055	0.0055	0.0461
11	0.0012	0.0012	0.0416

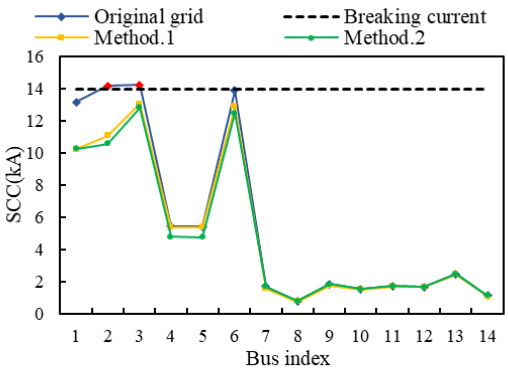

Fig. 5 *SCC of the IEEE 14-bus system*

6 are switched off. By comparison, the limitation of Method 2 is better than that of Method 1. Therefore, the decision of Method 2 is accurate and optimal.

Finally, this paper concludes that the error of method will disturb the decision of transmission switching in small-scale systems. The reason is that each line has a serious impact on the whole grid in smaller systems.

4.2 Limitation of SCC in the IEEE 57-bus system

In this paper, the parameters of the IEEE 57-bus system are shown as follows: $S_B = 100$ MVA, $U_B = 220$ kV and the maximal breaking current of circuit interrupter is 63 kA, and the per-unit value of sub-transient reactance (X_d'') of generators converts to system and is presented in Table 3.

The framework of the IEEE 57-bus system is shown in Fig. 6, and some important weighted sensitivity coefficients of the transmission lines in the two methods are presented in Table 4. Although s_k is varying in the modified grid, the decision of transmission switching is the same in the two methods.

Because of the same decision, the SCC limitation effect of the two methods is the same, as shown in Fig. 7.

As shown in Fig. 7, the limitation effect is observable and the same decision is that line 1, line 2 and line 8 are switched off.

Table 3 Sub-transient reactance (X_d'') of generators of the IEEE 57-bus system

Generators	Gen. 1	Gen. 2	Gen. 3	Gen. 6	Gen. 8	Gen. 9	Gen. 12
X_d''	0.1219	0.04	0.0577	0.0943	0.117	0.439	0.877

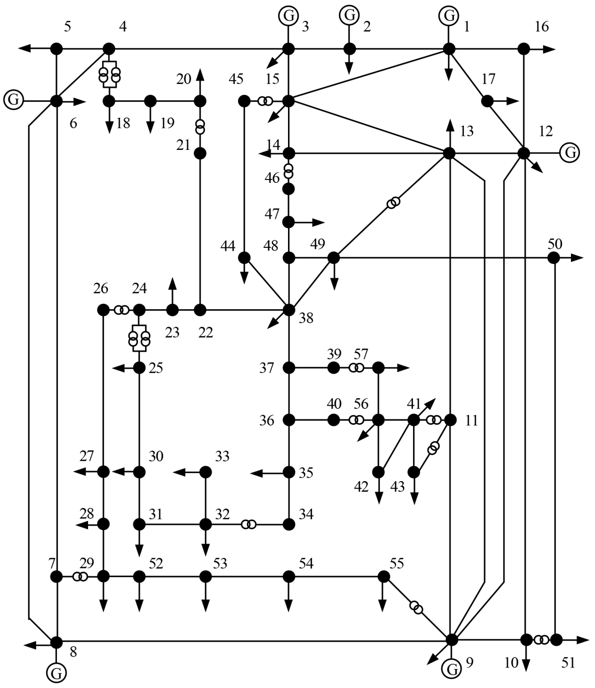

Fig. 6 *Diagram of the IEEE 57-bus system*

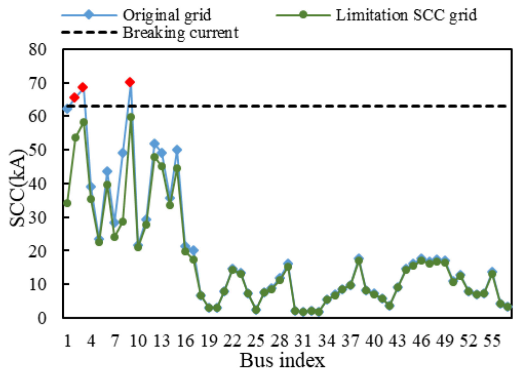

Fig. 7 *SCC of the IEEE 57-bus system*

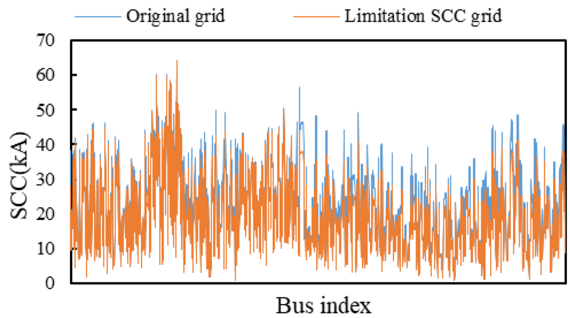

Fig. 8 *SCC of Northwest China Power Grid*

Table 4 Weighted sensitivity coefficients of the IEEE 57-bus system

Branch	Method 1	Method 2-I	Method 2-II	Method 2-III
1	**4.4619**	**4.4619**	0	0
2	**3.7934**	3.7934	**9.1889**	0
3	1.0849	1.0849	5.4801	10.0039
4	0.2776	0.2776	4.7196	9.3989
5	0.407	0.407	4.8393	9.4956
6	0.2908	0.2908	4.7595	9.4682
7	0.2594	0.2594	4.7238	9.4319
8	**2.296**	2.296	6.7516	**11.4413**
9	0.483	0.483	4.8843	9.5977
10	0.7216	0.7216	5.0756	9.7671

This paper concludes that the error of method would not disturb the decision of transmission switching in large-scale systems. The reason is that each line has a minor impact on the whole grid in larger systems. Therefore, Method 1 should be used to solve large-scale systems.

4.3 Limitation of SCC in Northwest China Power Grid

Northwest China Power Grid has multiple voltage levels, but this paper is only concerned about the SCC limitation of 220 kV voltage level.

The SCC limitation effect is shown in Fig. 8.

As shown in Fig. 8, transmission switching disassembles the electromagnetic ring grid and the SCC limitation effect is observable.

5 Conclusions

This paper focuses on studying the error of SCC influencing the decision of transmission switching selection in different power grid scales. The set of lines selection method and single and multiple lines selection method are compared and the improved sensitivity analysis method is proposed, which combines the advantages of the two methods. The set of lines selection method is suitable for the large-scale grid, while single and multiple lines selection method is suitable for the small-scale grid. Essentially, the proportion of transmission switching in the grid determines whether the error affects the decision or not. The effectiveness of the model and solution method is validated in cases.

6 Acknowledgments

This work is supported in part by State Grid Science & Technology Project: Research on Morphologies and Pathways of Future Power System and Key Research and Development Program of Shaanxi denominated ‘Research on Key Technology of Optimal Operation and Control of Power System with High Renewable Energy Penetration’ under Grant 2017ZDCXLGY-02-03.

7 References

[1] Chen, L.: ‘Prediction for magnitude of short circuit current in power distribution system based on ANN’. Proc. Int. Symp. Computer Science and Society, Kota Kinabalu, Malaysia, July 2011, pp. 130–133

[2] Schmitt, H.: ‘Fault current limiters report on the activities of CIGRE WG A3.16’. Proc. Power and Energy Society General Meeting, Montreal, Canada, June 2006, pp. 1–5

[3] Yang, D., Zhao, K., Liu, Y.: ‘Coordinated optimization for controlling short circuit current and multi-infeed DC interaction’, *J. Mod. Power Syst. Clean Energy*, 2014, **2**, (4), pp. 374–384

[4] Erkhan, F.: ‘Factors affecting values of short-circuit current levels in electrical power engineering systems’, *IEEE Trans. Power Syst.*, 2003, **8**, (6), pp. 15–21

[5] Janowski, T., Wojtasiewicz, G.: ‘Possibility of using the 2G HTS superconducting transformer to limit short-circuit Currents in power network’, *IEEE Trans. Appl. Supercond.*, 2012, **22**, (3), pp. 497–516

[6] Quaia, S., Tosato, F.: ‘Powersupply quality improvement by short-circuit current limitation on distribution nets’, *Int. J. Model. Simul.*, 1993, **15**, (1), pp. 1–7

[7] Fisher, E., O'Neill, R., Ferris, M.: ‘Optimal transmission switching’, *IEEE Trans. Power Syst.*, 2008, **23**, (3), pp. 1346–1355

[8] O'Neill, R., Baldick, R., Helman, U., *et al.*: ‘Dispatchable transmission in RTO markets’, *IEEE Trans. Power Syst.*, 2005, **20**, (1), pp. 171–179

[9] Hedman, K., Oren, S., O'Neill, R.: ‘A review of transmission switching and network topology optimization’. Proc. Power and Energy Society General Meet., Detroit, USA, July 2011, pp. 1–7

[10] Chu, C., Herbert, H.: 'Complex networks theory for modern smart grid applications: a survey', *IEEE J. Emerg. Sel. Top. Circuits Syst.*, 2017, **7**, (2), pp. 177–191
[11] Ruiz, P., Foster, J.M., Rudkevich, A., *et al.*: 'Tractable transmission topology control using sensitivity analysis', *IEEE Trans. Power Syst.*, 2012, **27**, (3), pp. 1550–1559
[12] Fuller, J., Ramasra, R., Cha, A.: 'Fast heuristics for transmission-line switching', *IEEE Trans. Power Syst.*, 2012, **27**, (3), pp. 1377–1386
[13] Rolim, J., Machado, L.: 'A study of the use of corrective switching in transmission systems', *IEEE Trans. Power Syst.*, 2002, **14**, (1), pp. 336–341
[14] Zhang, Y., Cai, Z., Li, A., *et al.*: 'An optimization algorithm for short-circuit current limitation of 500 kV power grid by adjusting power grid configuration', *Autom. Electr. Power Syst.*, 2009, **33**, (22), pp. 34–39
[15] Yang, Z., Zhong, H., Xia, Q., *et al.*: 'Optimal transmission switching with short-circuit current limitation constraints', *IEEE Trans. Power Syst.*, 2016, **32**, (2), pp. 1278–1288