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Evaluation of high-voltage AC cable grounding systems based on the real-time monitoring and theoretical calculation of grounding currents

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Abstract: For high-voltage (HV) AC cable transmission systems, the metal sheaths of three separate single-core cables are cross-bonded at each end of the cable section, to suppress the induced voltages in sheaths. The status of HV cable grounding systems is, therefore, an important consideration for power utilities. This study presents the status evaluations of 93 cable grounding systems in Beijing, obtained using the standards established by State Grid Corporation of China. As a result, 13 of these systems were classified as abnormal or defective. Additionally, a theoretical calculation of grounding currents was proposed and these 13 systems are re-evaluated by comparing the calculated and measured values of certain parameters. Based on this work, the authors propose a modified evaluation standards. It is indicated that the absolute value of grounding current (|*I*|) during a given 24-hr period has no relationship with the status of grounding system, and the ratio of grounding current to load current (*K*) at the time of maximum load current could be used as a status indicator instead of *K* at some other time, in order to avoid possible incorrect evaluations due to light load conditions.

1 Introduction

For high-voltage (HV) AC cable transmission systems, three separate single-core cables are frequently used instead of three-core cables. In practise, to suppress the induced voltages in sheaths, metal sheaths of HV cables are cross-bonded at each end of the cable section. The cross-bonding introduces return paths for the grounding currents [1, 2]. It is expected that, as a result of cross-bonding, the voltages induced in the metal sheaths will not exceed the limit specified in GB50217-2007 [3], and the grounding currents will be minimised, leading to less heat generation in the metal sheaths [4, 5].

However, the effectiveness of the grounding may be reduced due to water seepage into cross-connected boxes, failure of outer sheath insulation, or damages by termites, causing more heat emission from the metal sheaths and reduction of the current carrying capacity of HV cables [6, 7]. Marzinotto and Mazzanti [8] reported the feasibility of cable sheath fault detection by monitoring grounding currents at the ends of cross-bonding sections. Dong *et al.* [9, 10] established a numerical model to simulate the currents in cross-bonded cable sheaths and then analysed the sheaths currents under typical fault conditions, including an open-circuit fault in a metal sheath, short-circuit fault in cross-bonded boxes and short-circuit faults due to the breakdown between metal sheaths in joints. The status of HV cable grounding systems evaluated by grounding currents is, therefore, an important consideration for HV cables [11–13]. Status evaluation standards for cable grounding systems in Beijing have been established based on data obtained from real-time monitoring of grounding currents over the period 2010–2012, in accordance with the relevant standards Q/GDW 456-2010 established by State Grid Corporation of China (SGCC) [4]. However, some erroneous judgments resulted from the application of these standards, which should, therefore, be modified.

In this paper, we present the status evaluations of 93 cable grounding systems in Beijing, obtained using the standards established by SGCC. Thirteen of these systems were classified as abnormal or defective. A theoretical calculation of grounding currents was proposed. These 13 systems are re-evaluated by comparing the calculated and measured values of certain parameters. Based on this work, we propose a modification of SGCC evaluation standards.

2 Initial status evaluation of HV cable grounding systems

Online monitoring of HV cable grounding currents began in Beijing in 2010, covering 91 220 kV cables and 2 110 kV cables. The monitoring data were uploaded to the operation and monitoring centre of the cable network, and combined with cable loading data to enable real-time monitoring of the HV cable grounding systems. The status evaluation standards for cable grounding systems established by SGCC appear in Table 1. The initial status evaluation of the grounding systems of the 93 cables mentioned above, carried out using Table 1 standards, indicated that ten of the 220 kV cables were abnormal and two were defective, while one of the 110 kV cables was abnormal.

Using K and $|I|$ as defined above, the 13 abnormal or defective grounding systems may be divided into three groups (Cases I, II and III). Certain numerical characteristics of each case are given in Table 2. $K_{\max}$ and $K_{\min}$ are, respectively, the maximum and minimum values of K recorded over a given 24-hr period, and $|I_{\min}|$ is the minimum value of $|I|$ recorded over the same 24-hr period. The variations of K and $|I|$ over a 24-hr period for the typical Cases I, II and III grounding systems are shown in Fig. 1. $K_{\max}$ and $K_{\min}$ are, respectively, the maximum and minimum values of K recorded over a given 24-hr period, and $|I_{\min}|$ is the minimum value of $|I|$ recorded over the same 24-hr period.

3 Theoretical calculation of grounding current

In the HV cable cross-bonding systems, the metal sheath of a major cable section is divided into three minor sections. The metal sheaths of each minor cable section are cross-connected so as to approximately neutralise the total induced voltage in three consecutive sections, as shown in Fig. 2 [1].

The grounding currents through the metal sheaths have capacitive and induced components, the total current being the

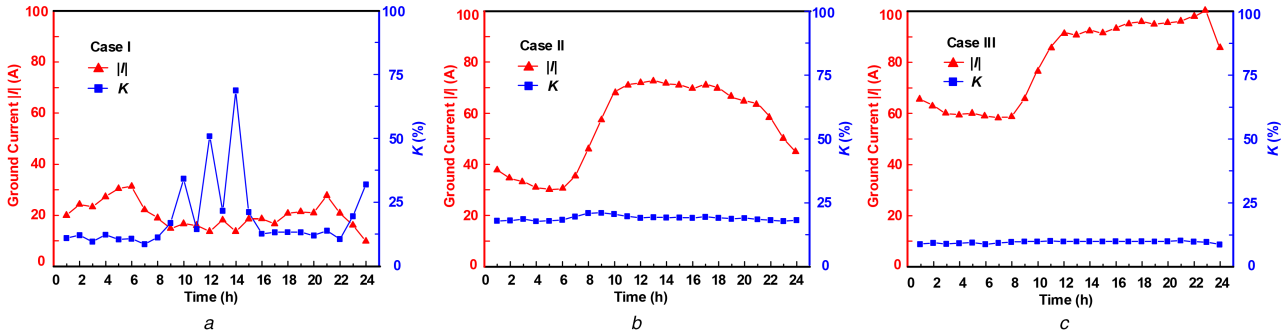

Fig. 1 *Variation of K and |I| over a 24-hr period for typical Cases I, II and III grounding systems*
(a) Case I, ***(b)*** Case II, ***(c)*** Case III

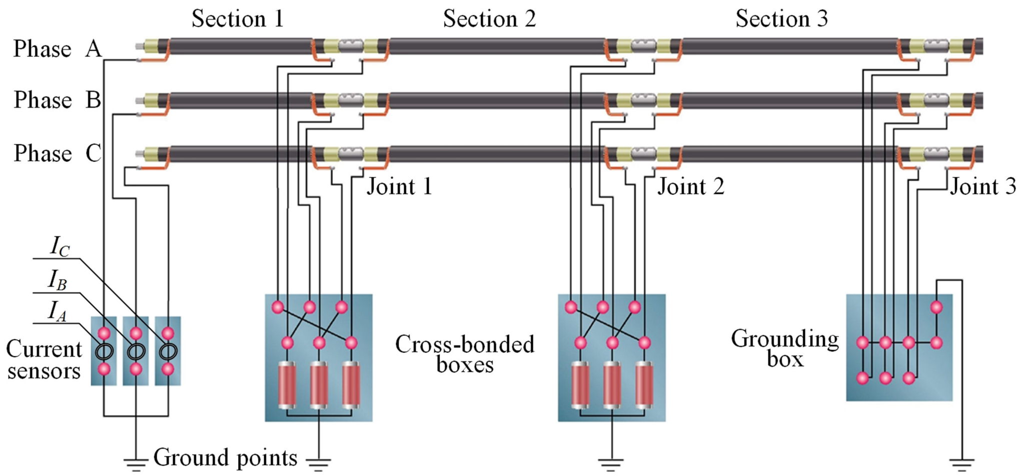

Fig. 2 *Cross-bonded cable system circuit*

Table 1 Status evaluation criteria for cable grounding systems established by SGCC

Status	Criteria
normal	Each of the following conditions must be satisfied over a 24-hr period:
	(1) |*I*| = absolute value of grounding current <100 A;
	(2) *K* = ratio of grounding current to load current in terms of percentage <20%;
	(3) Ratio of maximum to minimum single-phase grounding current <3.
abnormal	One or more of the following conditions must be satisfied over a 24-hr period:
	(1) |*I*| = absolute value of grounding current ≥100 A and ≤200 A;
	(2) *K* = ratio of grounding current to load current in terms of percentage ≥20% and ≤50%;
	(3) Ratio of maximum to minimum single-phase grounding current ≥3 and ≤5.
defective	One or more of the following conditions must be satisfied over a 24-hr period:
	(1) |*I*| = absolute value of grounding current >200 A;
	(2) *K* = ratio of grounding current to load current in terms of percentage >0.5;
	(3) Ratio of maximum to minimum single-phase grounding current >5.

Table 2 Numerical characteristics of thirteen abnormal or defective grounding systems

Case	Numerical characteristics	Number
I	$K_{max}/K_{min} \geq 2.0 K_{max} \geq 20\% \lvert I_{min}\rvert < 20.00$ A	6
II	$K_{max}/K_{min} < 2.0 K_{max} \geq 20\% \lvert I_{min}\rvert \geq 20.00$ A	5
III	$K_{max}/K_{min} < 2.0 K_{max} < 20\% \lvert I_{min}\rvert \geq 20.00$ A	2

vector sum of the capacitive and induced components. We may write

$$\begin{aligned} I_A &= I_{CA} + I_{IA} \\ I_B &= I_{CB} + I_{IB} \\ I_C &= I_{CC} + I_{IC} \end{aligned} \tag{1}$$

where I_A, I_B and I_C are, respectively, the total grounding currents in phases A, B and C, I_{CA}, I_{CB} and I_{CA} are the capacitive components and I_{IA}, I_{IB} and I_{IC} are the induced components.

The capacitive components are given by

$$\begin{aligned} I_{CA} &= \mathrm{j}\omega C U_A \times L \\ I_{CB} &= \mathrm{j}\omega C U_B \times L \\ I_{CC} &= \mathrm{j}\omega C U_C \times L \end{aligned} \tag{2}$$

where U_A, U_B, U_C are the phase voltages, and L is the total length of the three cable sections. C is the capacitance per unit length of the cable given by

$$C = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln(D_i/D_c)} \tag{3}$$

where ε_r is the relative permittivity of the cable insulation (2.6 for XLPE), ε_0 is the permittivity of vacuum, D_i is the outer diameter of the insulation layer, and D_c is the outer diameter of the conductor core (including the inner semi-conductive layer).

The cross-bonded cables model shown in Fig. 3 was used to calculate the induced components of the grounding currents. R_{d1} and R_{d2} are the ground resistances at the ends of the major cable sections. Z_{o1}, Z_{o2} and Z_{o3} are the resistances of the metal sheaths of each cable segment, I_{IE} is the earth return current, and V_{IAi}, V_{IBi} and V_{ICi} ($i = 1, 2, 3$) are the induced voltages in the metal sheaths

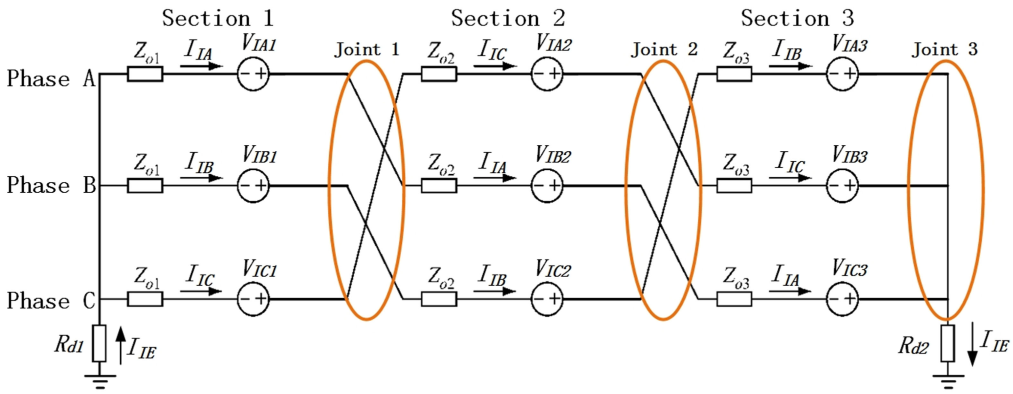

Fig. 3 *Numerical model of cross-bonded cables circuit*

of each cable section. This nomenclature is elaborated in detail in [14, 15].

Some simplifications are made in this numerical model, i.e.

(a) The V_{IAi}, V_{IBi} and V_{ICi} are induced by the load currents in three-phase cable and the circuit currents in metal sheaths of the other two phases. The mutual coupling effects of adjacent cable circuits sharing the same cable trench are ignored, in view of the spacing of different cable circuits.

(b) In cross-bonded joints, co-axial cables are used to connect sheaths to cable cross-bonded or grounding boxes. The mutual coupling effects of circuit currents in a co-axial cable are neglected.

According to Kirchhoff laws, it follows from Fig. 3 that

$$\begin{aligned}(Z_{o1}+Z_{o2}+Z_{o3})\times I_{IA}+(R_{d1}+R_{d2})\times I_{IE}&=V_{IA1}+V_{IB2}+V_{IC3}\\(Z_{o1}+Z_{o2}+Z_{o3})\times I_{IB}+(R_{d1}+R_{d2})\times I_{IE}&=V_{IB1}+V_{IC2}+V_{IA3}\\(Z_{o1}+Z_{o2}+Z_{o3})\times I_{IC}+(R_{d1}+R_{d2})\times I_{IE}&=V_{IC1}+V_{IA2}+V_{IB3}\\I_{IA}+I_{IB}+I_{IC}&=I_{IE}\end{aligned} \tag{4}$$

The relationship between the induced currents and the induced voltages is given by the matrix equation [14, 15]:

$$\begin{bmatrix}Z_{11}&Z_{12}&Z_{13}\\Z_{21}&Z_{22}&Z_{23}\\Z_{31}&Z_{32}&Z_{33}\end{bmatrix}\begin{bmatrix}I_{IA}\\I_{IB}\\I_{IC}\end{bmatrix}=\begin{bmatrix}V_{IA}\\V_{IB}\\V_{IC}\end{bmatrix} \tag{5}$$

where

$$\left.\begin{aligned}Z_{xy}&=R_d+R_{d1}+R_{d2} & (x\neq y)\\Z_{xy}&=Z_{o1}+Z_{o2}+Z_{o3}+R_d+R_{d1}+R_{d2} & (x=y)\end{aligned}\right\}(x,y=1,2,3)$$

$$\begin{aligned}V_{IA}&=V_{IA1}+V_{IB2}+V_{IC3}\\V_{IB}&=V_{IB1}+V_{IC2}+V_{IA3}\\V_{IC}&=V_{IC1}+V_{IA2}+V_{IB3}\end{aligned}$$

All the elements in (5) are complex numbers and can be separated into real and imaginary parts. Representing the real parts with a single dash (′), and the imaginary parts with a double dash (″), we have (see (6)) The relationships between the induced currents and the induced voltages are then

$$\begin{bmatrix}Z'_{11}&Z'_{12}&Z'_{13}&-Z''_{11}&-Z''_{12}&-Z''_{13}\\Z''_{11}&Z''_{12}&Z''_{13}&Z'_{11}&Z'_{12}&Z'_{13}\\Z'_{21}&Z'_{22}&Z'_{23}&-Z''_{21}&-Z''_{22}&-Z''_{23}\\Z''_{21}&Z''_{22}&Z''_{23}&Z'_{21}&Z'_{22}&Z'_{23}\\Z'_{31}&Z'_{32}&Z'_{33}&-Z''_{31}&-Z''_{32}&-Z''_{33}\\Z''_{31}&Z''_{32}&Z''_{33}&Z'_{31}&Z'_{32}&Z'_{33}\end{bmatrix}\begin{bmatrix}I'_{IA}\\I'_{IB}\\I'_{IC}\\I''_{IA}\\I''_{IB}\\I''_{IC}\end{bmatrix}=\begin{bmatrix}V'_{IA}\\V''_{IA}\\V'_{IB}\\V''_{IB}\\V'_{IC}\\V''_{IC}\end{bmatrix} \tag{7}$$

The real and imaginary parts of I_{IA}, I_{IB} and I_{IC} can be calculated using Gaussian elimination and step-by-step iteration. The amplitudes and phase angles of I_A, I_B and I_C can then be calculated from (1), as well as the ratio K of grounding current to load current. Then the theoretical calculation of grounding current is verified by a normal cable grounding system. The measured and calculated grounding currents of phase C over a 24-hr period are shown in Fig. 4. The results show a good consistency during the 24-hr period, indicating the feasibility of the numerical model of grounding currents. The computations outlined above have been used to evaluate the status of HV cable grounding systems by comparing the calculated and measured values of the ratio K of the grounding current to the load current.

In China, some HV cables often share the same trenches, resulting in a mutual coupling effect of circuit currents between the adjacent cable cores and metal sheaths, which is ignored in the theoretical calculation of induced components of grounding current outlined above. The mutual coupling effects of adjacent cable circuits sharing the same cable trench may have a significant effect on the grounding currents, especially when the adjacent cable is in a state of the high load, thus causing the different between the measured and calculated grounding currents. This may be the main reason for the differences between the measured and calculated grounding currents during 0–7 h and 24 h, as shown in Fig. 4. Therefore, the differences of measured and calculated K at a given

$$\begin{aligned}V'_{IA}&=Z'_{11}I'_{IA}-Z''_{11}I''_{IA}+Z'_{12}I'_{IB}-Z''_{12}I''_{IB}+Z'_{13}I'_{IC}-Z''_{13}I''_{IC}\\V''_{IA}&=Z''_{11}I'_{IA}+Z'_{11}I''_{IA}+Z''_{12}I'_{IB}+Z'_{12}I''_{IB}+Z''_{13}I'_{IC}+Z'_{13}I''_{IC}\\V'_{IB}&=Z'_{21}I'_{IA}-Z''_{21}I''_{IA}+Z'_{22}I'_{IB}-Z''_{22}I''_{IB}+Z'_{23}I'_{IC}-Z''_{23}I''_{IC}\\V''_{IB}&=Z''_{21}I'_{IA}+Z'_{21}I''_{IA}+Z''_{22}I'_{IB}+Z'_{22}I''_{IB}+Z''_{23}I'_{IC}+Z'_{23}I''_{IC}\\V'_{IC}&=Z'_{31}I'_{IA}-Z''_{31}I''_{IA}+Z'_{32}I'_{IB}-Z''_{32}I''_{IB}+Z'_{33}I'_{IC}-Z''_{33}I''_{IC}\\V''_{IC}&=Z''_{31}I'_{IA}+Z'_{31}I''_{IA}+Z''_{32}I'_{IB}+Z'_{32}I''_{IB}+Z''_{33}I'_{IC}+Z'_{33}I''_{IC}\end{aligned} \tag{6}$$

sampling time may be not a reliable indication for status evaluation. In order to avoid the erroneous judgments, the condition of the cable grounding system can reliably be considered normal, when the calculated and measured values of the average value of K agree within 5% over a 24-hr period. Otherwise, the condition must be considered abnormal. The evaluation criteria for cable grounding systems according to the theoretical calculation are shown in Table 3. K_{ical} and K_{imes} present the calculated and measured values over a 24-hr period, respectively. Adopting this criterion, the 13 abnormal or defective cable grounding systems, which were initially evaluated as abnormal and defective, were re-evaluated, thus investigating the reliability of the status evaluation standards shown in Table 1. The results indicated that 8 of the 13 cable systems, which were classified as Cases I and III, were normal, and the 5 systems classified as Case II were abnormal.

3.1 Case I characteristics

Six 220 kV grounding systems were classified as Case I, as shown in Table 2. Each of these six 220 kV grounding systems was classified as defective because the measured K exceeded 0.50 at various times during a 24-hr period. Out of the six systems, the phase B of one cable grounding system is employed to make an analysis in this paper. The calculated and measured values of K, over this 24-hr period, are compared in Fig. 5*a*. It is indicated that the calculated and measured values of the average value of K for the particular system K agree within 5% over the 24-hr period, suggesting that the status of this particular system is normal, contrary to the initial status classification as defective. The same agreement was observed for each of the other five Case I systems.

The sudden increases in K during the 10–14 h and 20–24 h periods are quantitatively consistent with the very much larger decreases in load current during the same time interval, as shown in Fig. 5*b*. It can be observed that the minimum load current was <10% of the maximum load current. The minimum load current was at 14 h, and the I_C (capacitive component) and I_I (induced component) was calculated and shown in Table 4, as well as the $|I|$. It is indicated that under light load conditions, the induced current is much less than the capacitive current, in which case the capacitive current is approximately equal to the total grounding current, leading to a sharp increase of K. Each of the other five Case I systems also showed a sudden decrease in load current during 24 h periods. It follows that the reason for the sharp increase of K is the marked decrease in load current.

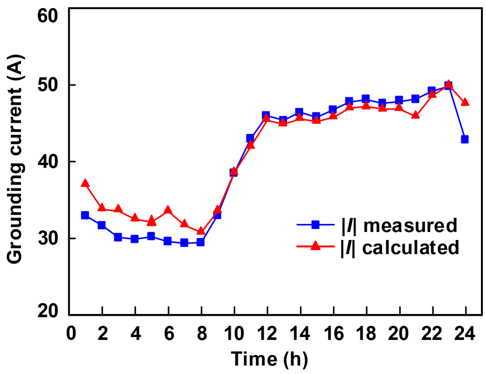

Fig. 4 *Measured and calculated grounding currents of phase C in a cable grounding system over a 24-hr period*

Table 3 Status evaluation criteria for cable grounding systems according to the theoretical calculation

Status	Criteria
normal	$\frac{1}{24}\sum_{i=1}^{24}\lvert K_{\rm ical}-K_{\rm imes}\rvert < 5\%$
abnormal	$\frac{1}{24}\sum_{i=1}^{24}\lvert K_{\rm ical}-K_{\rm imes}\rvert \geq 5\%$

3.2 Case II characteristics

Five cable grounding systems were classified as abnormal or defective, according to Table 1, because the measured K exceeded 0.2 at some time during the 24 h period. The measured and calculated values of K for one particular system are compared in Fig. 6*a*. It can be observed that the K was 0.21 during the 8–9 h period, exceeding 0.20. Therefore, the cable grounding system was classified as abnormal, according to Table 1. As shown in Fig. 6*a*, the measured and calculated values of K differed by much more than 5% throughout the 24-hr period for this particular system, strongly suggesting that it was not normal. Additionally, in Fig. 6*b*, there does not yet exist light load conditions as shown in Fig. 5*b*. Comparable differences were observed for each of the other four Case II systems, suggesting that they were also not normal.

3.3 Case III characteristics

Two grounding systems were classified as abnormal, according to Table 1, because the measured values of $|I|$ exceeded 100 A during the 22–23 h period. However, the measured and calculated values of the average value of K for one of these systems agreed within 5% during the 24-hr period as shown in Fig. 7*a*, suggesting that this system was normal. Additionally, in Fig. 7*b*, there does not yet exist light load conditions as shown in Fig. 4*b*. A similar agreement between the measured and calculated values of $|I|$ and K was

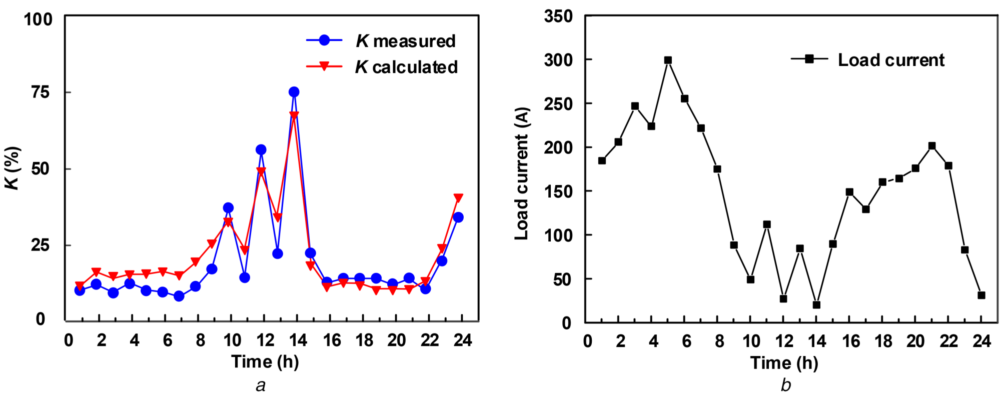

Fig. 5 *Measured and calculated K for a Case I grounding system, and the load current, over a 24-hr period*
(a) Measured and calculated K, ***(b)*** Load current

Table 4 Measured and calculated K under the lowest load current for the Case I grounding system

Load current, A	I_C, A	I_I, A	$\lvert I\rvert_{cal}$, A	$\lvert I\rvert_{mes}$, A	K_{cal}	K_{mes}
20.1	6.7	0.5	6.9	8.0	0.65	0.76

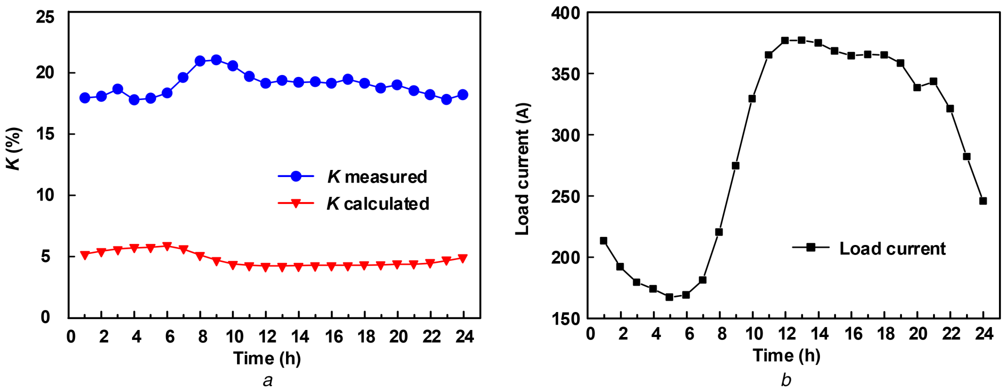

Fig. 6 *Measured and calculated K for a Case II grounding system, and the load current, over a 24-hr period*
(a) Measured and calculated *K*, ***(b)*** Load current

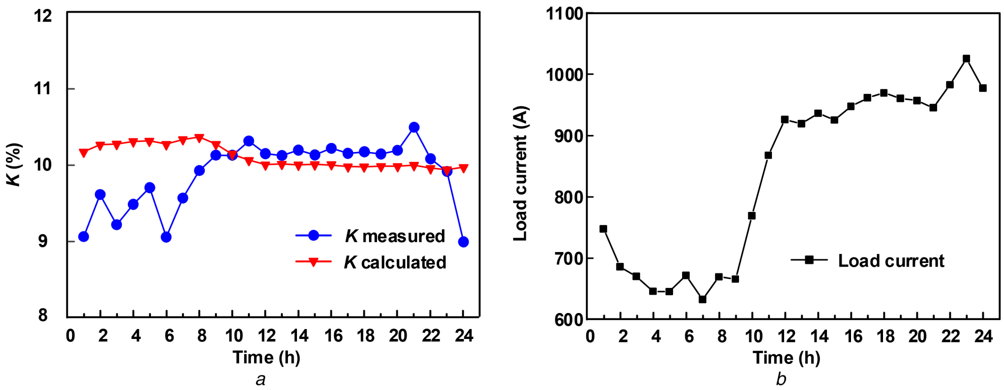

Fig. 7 *Measured and calculated K for a Case III grounding system, and the load current, over a 24-hr period*
(a) Measured and calculated *K*, ***(b)*** Load current

Table 5 Modified status evaluation criteria for cable grounding systems

Status	Criteria
normal	$K_{MLC} < 20\%$
abnormal	$20\% \leq K_{MLC} \leq 50\%$
defective	$50\% \leq K_{MLC} \leq 100\%$

K_{MLC} is the value of K at the time of maximum load current during a given 24-hr period.

Table 6 Evaluation of ninety-three cable grounding systems using the modified criteria

Voltage grade, kV	Status of cable grounding systems			
	Normal	Abnormal	Defective	Total
220	87	4	0	91
110	1	1	0	2

observed for the other Case III system. Based on our prior experience, we believe that large $|I|$ values (of order 100 A in this case) may be due to inaccurate physical arrangements of cable grounding systems during construction, leading to a failure of cross-bonding. Therefore, it is suggested that the condition 100 A $\leq |I| \leq$ 200 A is not necessarily a reliable indication that the condition of a grounding system is abnormal.

4 Discussion and modification of status evaluation standards

In the six Case I cable systems, the measured K greatly exceeded 0.5 at some time during the 24-hr period (Fig. 5*a*), so that, using Table 1, these systems would be classified as defective. However, the calculated and measured values of the average value of K agreed within 5% over the same 24-hr period. According to the proposed criteria based on the theoretical calculation of grounding current, these systems would be classified as normal. An explanation for the high measured K values, in terms of light load conditions, was suggested above.

Using Table 1, the five Case II systems were classified as abnormal because the measured K lay in the range of 0.2–0.5 at some time during the 24-hr period. According to the proposed new criteria, these systems should again be classified as abnormal, since the measured and calculated values of K and $|I|$ differed by much more than 5% over the entire measurement period.

In the two Case III systems, the measured $|I|$ exceeded 100 A at some time during the 24-hr period. These systems would, therefore, be classified as abnormal, using the criteria in Table 1. However, according to the proposed criteria, these systems should be classified as normal since the measured and calculated values of the average value of K agreed within 5% during the 24-hr period. Therefore, there is no direct relationship between $|I|$ and the status of the grounding system. It is suggested above that large $|I|$ values (exceeding 100 A) may be due to inaccurate physical arrangements of cable grounding systems during construction, for example imbalanced length or spacing of three cable sections due to the limitation of the cable trench.

In order to avoid possible incorrect classifications due to light load conditions, we suggest that K_{MLC}, defined as the value of K at the time of maximum load current during a given 24-hr period, be used as a status indicator instead of K at some other time. It is verified that, for each of the five Case II systems, K_{MLC} exceeded 0.2 during the 24-hr period, as shown in Fig. 6 for one of these systems. These five abnormal cable grounding systems are further verified by the status evaluation criteria based on the theoretical calculation shown in Table 3, in order to judge the criteria as reliable. The comparitive results of these five cable grounding systems all suggest that there are great deviations between the measured and calculated values of grounding currents during any measuring period. We, therefore, propose the modified status criteria shown in Table 5, based on the above analyses and the criteria established by the SGCC.

The status of each of the ninety-three grounding systems was evaluated using these modified criteria. The results are shown in Table 6. 94.6% of the systems were classified as normal, compared with 86.0% using Table 1. The status evaluation results show that, Beijing HV cable metal sheath grounding system is smooth. For the currently operating and new HV cables, the effective technical measures to improve the cable grounding system status level include the installation of online grounding current monitoring system, and the selection of overall compound seal grounding box and cross-connect box.

5 Conclusions

i. New criteria for evaluation of the status of the HV cables grounding systems have been proposed, based on comparison of the calculated and measured values of the grounding current/load current ratio K. Assuming that agreement between the measured and calculated values of $|I|$ and K within 5% is accepted as a reliable indication that the status of a grounding system is normal.
ii. Based on the status evaluation criteria suggested by the Electric Power Company, the 93 HV cable grounding systems in Beijing was evaluated, and the 13 abnormal or defective grounding systems may be divided into three groups based on the numerical characteristics of $|I|$ and K. It is indicated that $|I|$ have no relationship with the status of grounding system, and K can be directly used to indicate whether the status of grounding system is normal or not. It is suggested that the value of K at the time of maximum load current during a given 24-hr period, could be used as a status indicator instead of K at some other time, in order to avoid possible incorrect classifications due to light load conditions.
iii. The status evaluation results based on real-time monitoring data of grounding current show that, Beijing HV cable metal sheath grounding system is smooth. For the currently operating and new HV cables, the effective technical measures to improve the cable grounding system status level include the installation of online grounding current monitoring system, and the selection of overall compound seal grounding box and cross-connect box.

6 Acknowledgments

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7 References

[1] IEEE Std.: 'IEEE Guide for Bonding Shields and Sheaths of Single-Conductor Power Cables Rated 5 kV through 500 kV', 2014

[2] Jung, C.K., Lee, J.B., Kang, J.W., *et al.*: 'Sheath current characteristic and its reduction on underground power cable systems'. Proc. of IEEE Power Engineering Society General Meeting, San Francisco, CA, USA, June 2005, pp. 2562–2569

[3] IEC 287-1-1: 'Electric Cables – Calculation of the Current Rating, Part 1: Current Rating Equations (100% Load Factor) and Calculations of Losses, Section 1: General', 1994

[4] Q/GDW 456: 'Guide for Condition Evaluation of Power Cable', State Grid Corporation of China, 2010

[5] Chen, L.R., Rong, X., Luo, J.H.: 'Technique research on the online detection and restraint of the induced voltage and circulating current on the metal sheath of 35 kV 630 mm^2 single-core XLPE cable'. Proc. Int. Conf. Electricity Distribution, Piscataway, NJ, USA, September 2010, pp. 1–6

[6] Peng, F.D., Yan, L., Li, X., *et al.*: 'The design of distributed on-line monitoring system for metal sheath's circulating current of cross-linked power cables'. Proc. Int. Conf. High Voltage Engineering and Application, Chongqing, China, November 2008, pp. 562–565

[7] Yan, L., Peng, F.D., Chen, X.L., *et al.*: 'Study on sheath circulating current of cross-linked power cables'. Proc. Int. Conf. High Voltage Engineering and Application, Piscataway, NJ, USA, November 2008, pp. 645–648

[8] Marzinotto, M., Mazzanti, G.: 'The feasibility of cable metal sheath fault detection by monitoring metal sheath-to-ground currents at the ends of cross-bonding sections', *IEEE Trans. Ind. Appl.*, 2015, **51**, (6), pp. 5376–5384

[9] Dong, X., Yang, Y., Zhou, C.K., *et al.*: 'On-line monitoring and diagnosis of HV cable faults by sheath system currents', *IEEE Power Deliv.*, 2017, **99**, pp. 1–9

[10] Dong, X., Yuan, Y., Gao, Z., *et al.*: 'Analysis of cable failure modes and cable joint failure detection via sheath circulating current'. IEEE Electrical Insulation Conf. (EIC), Philadelphia, PA, USA, June 2014, pp. 294–298

[11] Ma, H.Z., Song, J.G., Ni, X.R., *et al.*: 'Analysis of induced voltage in metal shield of power cable and research on its restraining technology based on asymmetric state'. Proc. Int. Conf. Electric Utility Deregulation and Restructuring and Power Technologies, Nanjing, China, April 2008, pp. 948–951

[12] Ma, H.Z., Song, J.G., Ju, P., *et al.*: 'Research on compensation and protection of voltage in metal shield of 110 kV power cable under three segments unsymmetrical state'. IEEE Power & Energy Society General Meeting, Pittsburgh, PA, USA, July 2008, pp. 1–5

[13] Rhodes, D.J., Wright, A.: 'Induced voltages in the sheaths of crossbonded a.c. cables', *Proc. Inst. Electr. Eng.*, 1966, **113**, (12), pp. 99–110

[14] Du, B.X., Li, Z.L., Wang, L.: 'The calculation of circulating current for the single-core cables in smart grid'. Proc. IEEE Innovative Smart Grid Technologies – Asia, Tianjin, China, May 2012, pp. 1–4

[15] Du, B.X., Li, Z.L., Zhang, K.: 'Calculation and application of 220 kV crosslinked polyethylene power cable grounding current', *High Volt. Eng.*, 2013, **39**, (5), pp. 1034–1039 (in Chinese)