SHEATH CIRCULATING CURRENT CALCULATIONS AND MEASUREMENTS OF UNDERGROUND POWER CABLES

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ABSTRACT

In this paper, a calculation method of the sheath circulating current is introduced, taking the different grounding types, laying environment, structural parameters of cables into account. Due to the parameters in practice, the circulating currents in sheath are calculated and measured under the conditions of single-point grounding and both-end crossbonded grounding. The possible causes, which lead to high circulating current, are discussed based on the calculation method.

KEYWORDS

Sheath circulating current; capacitance current; induced current

INTRODUCTION

With the development of high voltage and ultra-high voltage applications in power transmission systems in China, the single-core cables are usually used instead of three-core cables [1]. When the cables are in service, circulating currents flows in the sheaths. Large circulating current leads to the big loss in the sheaths and thus reduces the permissible current of the cables. Moreover, it will also enhance the danger in the cable maintenance and reduce the lifetime of the cables or cause the faults by the breakdown of insulation or cable jacket [2, 3]. Therefore, calculation on the sheath circulating currents and study on their characteristics are of importance for the maintenance of power cable system.

Under a common service condition, the sheath circulating current includes two parts: capacitance current and induced current. As the single-core cable is a cylindrical capacitance, the high-voltage side of the capacitance is the cable core, while the low-voltage side is the sheath of the cable. The current coupled by capacitance which is named capacitance current exists in the sheath, when AC load current flows in the cable core. The induced current appears in the sheath if there is induced voltage and the sheath is connected with the earth at more than one point, leading to a circuit loop for the induced current. The induced voltage is usually caused by the mixed laying method of the cables and different lengths between sections. It is also affected by the length of the cable, the layout type and the distance between cables. The several grounding points may be caused by the poor connection at the bonding point of lead sheaths, poor insulation of jackets, and so on.

The sheath of a long cable is divided into several sections, with the number of multiple times of three. And these sections are crossbonded together at each end of the cables to decrease the induced voltages and currents in the sheaths, shown in figure 1. In this condition, the phase difference of the induced voltages in each sheath section, such as A1B2C3, is 120°. Thus the total induced voltages in this circuit loop will be counteracted at the three sections, shown in Figure 2. The length of each section in figure 2 is same. But in practice, if the length of the sections is different, the induced current will increase obviously [4].
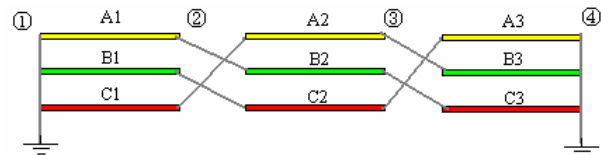

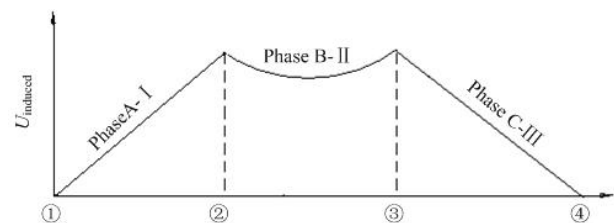**Figure 1: A schematic diagram of both-end crossbonded grouding three-phase cables**

Figure 2: The induced voltage in the sheath marked A1B2C3 in figure 1

In this paper, we present the calculation method of capacitance current and induced current in sheath of the single-core cable. Especially, according to the flowing path of the capacitance current in the case of the crossbonded both-end grounding, we provide an equivalent circuit to calculate the current values flowing at every site along the cables. Based on the method, the sheath current of several cables in service are calculated and measured, and the calculation error and its influence factors are analyzed.

CALCULATION METHOD

Calculation method of capacitance current

The single-core cable can be looked as a cylindrical capacitance. Its capacitance per unit length is known as [5]:

$$C = \frac{55.7\varepsilon * 10^{-12}}{\ln \dfrac{D_c + 2\Delta}{D_c}} \text{ F/m} \qquad [1]$$

where D_c represents the diameter of cable, Δ is the insulation thickness of cable, and ε is the relative dielectric constant of XLPE material with a value of about 2.5.

Because of the large resistance of XLPE insulation with an order about $10^{13} \sim 10^{15}$ Ω/m, the leakage current in insulation layers is much smaller than the capacitance current, and it can be ignored. Thus the capacitance current in the three single-core cables per unit length are given as:

$$\bar{I}_{ca} = j\omega C\bar{U}_a \quad \text{A/m}$$
$$\bar{I}_{cb} = j\omega C\bar{U}_b \quad \text{A/m} \qquad [2]$$
$$\bar{I}_{cc} = j\omega C\bar{U}_c \quad \text{A/m}$$

where $\bar{I}_{ca}$, $\bar{I}_{cb}$, $\bar{I}_{cc}$ represent the capacitance current in the three single-core cables per unit length respectively , $\bar{U}_a$, $\bar{U}_b$, $\bar{U}_c$ represent the phase voltage of phase A, B and C respectively, ω is the angular frequency of voltage.

Although the capacitance current of unit length can be calculated by the formula 2 whatever the grounding method of a cable is adopted, the total capacitance current of a full-length cable cannot be calculated by the same method, because it flows in different circuits in different grounding conditions, such as the single-point grounding and crossbonded both-end grounding. Under the former grounding condition, it is known that the capacitance in every unit of cable is paralleled. The total value of the capacitance current is equal to the multiplication of its value of per unit and the whole length of the cable. However, the total capacitance current of a whole cable under the latter condition is different and more complicated. Figures 3 (a) and (b) show the flowing path of the capacitance current and its corresponding equivalent circuit diagram, respectively. In figure 3(a), the point M and S represent the grounding site, K is a random point on the cable, and N is the end point. Because there are two grounding sites in figure 3(a), the capacitance current flows toward to them. Thus the branch circuits appear in the sheath, i.e. the KM branch and the KNS branch. In figure 3(b), i_c, i_1 and i_2 represent the total capacitance current, its part in the MK segment and part in the KS segment respectively.
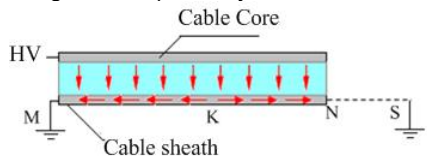
（a）**Flowing path of the capacitance current**
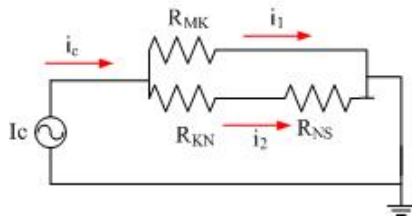
（b）**Equivalent circuit diagram**

Figure 3: Capacitance Current under the crossbonded both-end grounding condition

According to this equivalent circuit, the capacitance current in KM-line and KS-line are calculated in the following:

$$\bar{I}_1 = \frac{R_{KN} + R_{NS}}{R_{MK} + R_{KN} + R_{NS}} \cdot \bar{I}_c$$

$$\bar{I}_2 = \frac{R_{MK}}{R_{MK} + R_{KN} + R_{NS}} \cdot \bar{I}_c \qquad [3]$$

Calculation method of induced current

The inductance of per unit length sheath in a single-core cable can be calculated as [6]:

$$L_s = 2\ln\frac{2s}{D_s} * 10^{-7} \quad \text{H/m} \qquad [4]$$

The inductive voltage of the unit length is:

$$\bar{U}_s = -j\omega L_s \bar{I} \quad \text{V/m} \qquad [5]$$

where $\bar{I}$ represents the load current. Under the condition of balanced load for the three-phase cables, i.e. $\bar{I}_a + \bar{I}_b + \bar{I}_c = 0$, the inductive voltages in the sheaths of the tree separate single-core cables in unit length are:

$$\text{Phase A: } \bar{U}_{sa} = -j\bar{I}_a X_1 + j\bar{I}_c X_a \quad \text{V/m}$$
$$\text{Phase B: } \bar{U}_{sb} = j\bar{I}_a X_1 + j\bar{I}_c X_3 \quad \text{V/m} \qquad [6]$$
$$\text{Phase C: } \bar{U}_{sc} = -j\bar{I}_c X_3 + j\bar{I}_a X_b \quad \text{V/m}$$

In formula 6,

$$X_1 = 2\omega\ln\frac{2s_1}{D_s} * 10^{-7} \qquad \text{Ω/m}$$

$$X_3 = 2\omega\ln\frac{2s_2}{D_s} * 10^{-7} \qquad \text{Ω/m}$$

$$X_a = 2\omega\ln\frac{s_3}{s_1} * 10^{-7} \qquad \text{Ω/m} \qquad [7]$$

$$X_b = 2\omega\ln\frac{s_3}{s_2} * 10^{-7} \qquad \text{Ω/m}$$

where D_s represents the average diameter of sheath, s_1, s_2, s_3 are respectively the distances between phase A and phase B, phace B and phace C, phase C and phase A, shown in figure 4.
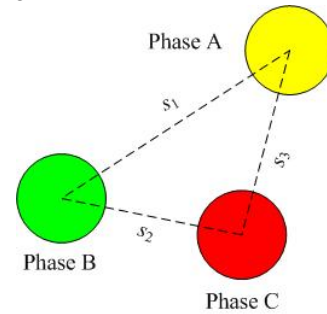

Figure 4: The distances of three phases

According to their equivalent circuit, the inductive voltage in the sections of a cable can be treated as connection in series. The total inductive voltage is equal to the multiplication of the unit voltage and the length of cable, just like the total capacitance current under the condition of single-point grounding. The corresponding induced current can be obtained by dividing the inductive voltage by the total impedance in the loop circuit. The impedance includes the grounding resistance, the resistance of

sheath and contact resistance at the middle connection sites.

The resistance of sheath per unit length accords to the following relations:

$$R_{s1} = \frac{\rho_s}{A_s}\left[1 + \alpha_s\left(\theta * \eta - 20\right)\right] \quad \Omega/m \qquad [8]$$

where ρ_s represents the resistivity of metal sheath material, A_s is the cross-sectional area of metal sheath, α_s is the temperature coefficient of the material, θ is the temperature of the conductor in service with a unit of centigrade, and η is the ratio of temperature of the sheath to the temperature of the conductor with a typical value in the range 0.7~0.8, which depends on the insulation thermal resistance [4]. The reactance of sheath of unit length is given by

$$X_s = 2\omega\ln\frac{2s}{D_s} * 10^{-7} \quad \Omega/m \qquad [9]$$

From the above analysis, it can be seen that sheath circulating current calculation methods are different under different grounding conditions. Under the condition of single point grounding, there is no induced current in the sheath because there is no flowing path for it although there is inductive voltage. As a result, the circulating current in metal sheath only consists of the capacitance current in this condition. However, under the condition of both-end crossbonded grounding, the induced current can flow in the sheath, the total current in it is equal to the vector sum of capacity current and the induced current. The angle between the two current parts is considered as the power angle approximately.

RESULTS AND DISCUSSIONS

According to the calculation methods, the capacitance current and induced current of some 110 kV and 220 kV in service are calculated. The studied cables are all produced in Huaxin Cable Factory in Hangzhou of China. The calculation results are compared with the measurements results, and errors are analyzed too.

Single point grounding

As mentioned above, under the condition of single point grounding, the circulating current is equal to the capacitance current in cable sheath.

Table 1 shows the structure parameters and lengths of two type cables: YJLW03-64/110kV-1×400mm^2(N0.1, 110kV) and YJLW03-127/220kV-1×1000 mm^2 (No.2, 220kV). The diameter of the cable core, the insulation thickness and the length of the cables are also presented.

Table 1: Structure parameters and lengths of Cables

Type	Diameter	Insulation Thickness	Length
No.1	26.5 mm	17.5 mm	1115 m
No.2	42.2 mm	24.0 mm	942 m

The calculation and measurement results of circulating current in each node of the cable sheath above are shown in table 2. The PG and DG in the table column named Grounding Mode stand for two kinds of grounding types, i.e., PG means grounding through a over-voltage

protection for power jacket and DG means groundling directly. The over-voltage protection makes the sheath insulated from the ground. In table 2, it can be found that the two cables are grounded at middle and insulated from ground at both ends.

Table 2 also shows that the calculation results are very close to the measurement results, with a maximum error less than 7%. Thus the calculation method can be applied to obtain the current in the sheath under the condition of single-point grounding.

Table 2 Sheath Circulating Current Calculation and Measurement Results

Type	Node	Grounding Mode	Calculation/Measurement (A)		
			I_A	I_B	I_C
No.1	1	PG	0.00	0.00	0.00
	2	DG	3.68/3.54	3.68/3.55	3.68/3.55
	3	PG	0.00	0.00	0.00
No.2	1	PG	0.00	0.00	0.00
	2	DG	6.89/6.46	6.89/6.71	6.89/6.83
	3	PG	0.00	0.00	0.00

Both-end crossbonded grounding

The both-end crossbonded grounding mode is also studied, which has been shown in Figure 1. The currents in the sheath of an 110kV cable marked No.3 (YJLW03-64/110kV-1×500 mm^2) and a 220kV cable marked No.4 (YJLW03 -127/220kV-1×1600mm^2) with this grounding condition are calculated. Their structure parameters and lengths are shown in table 3. The cables No.3 and No.4 both stand for three phase cables of one loop, and all the parameters of the cables from a loop are same.

Table 3 Structure parameters and lengths of cables

Type	Diameter	Insulation thickness	Length	Load current
No.3	30.0 mm	17.5 mm	1316m	61A
No.4	53.1 mm	24.0 mm	2912m	408A

The layout types of No.3 and No.4 cables are different. The three-phase cables of the former are laid in parallel with 100 mm neighborhood distance, while those of the latter are laid in a mode of an isoceles rectangle triangle with 350mm length of rectangle side. The No.3 cables are divided into three segments to cross bond shown in Figure 1, while the No.4 cables need to be divided into double three segments, because they are too long to divide into three segments, or the inductive voltage of each segment exceed the above limit of 50V.

According to the calculation method of induced current introduced in section 2.2, the inductive voltage can be calculated if the parameters of length, load current and layout distance of cables are given. The resistance and reactance values of the metal sheath can be calculated by formula 8 and 9. However, it's difficult to calculate or measure the loop circuit resistance of sheath under the normal service condition, because it contains several parts including ground resistance, sheath resistance and

bonding resistance. The values of the component resistance are estimated, taking 0.1Ω as an example in our approximate calculation. Besides, in the calculation of the vector sum of capacitance current and induced current, the angle between them corresponding to a power factor of 0.95 is used. The calculation and measurement results of each nodes cables No.3 and No.4 are shown in table 4 and table 5 respectively. CG in the tables represents crossboned grounding.

From table 4 and table 5, it can be seen that there are several nodes in cable No.3 and No.4 where the values of calculation and measurement are quite different under the condition of both-end crossbonded grounding. This may be due to the difference between the assumed resistance values of the nodes in our calculation and the actual values. It is also suggest that among the factors influencing the induced currents, the resistance in the loop circuit of the sheath plays the dominating role. If they could be measured effectively before the cables are put into service, the calculation will be more accurate. Moreover, the space between cables also affects the calculation results. In fact, cables No.3 are laid directly in the cable trench without fixed, so the space among cables is not exactly same along the cables, especially the space changes greatly in some position. This may also contribute to the difference between our calculation results and the practical situation.

Table 4 Calculation and measurement results of sheath currents in Cable No.3

Node	Grounding Mode	Calculation/Measurement (A)		
		I_A	I_B	I_C
1	DG	3.17/3.20	3.11/6.06	2.76/4.00
2	CG	2.83/4.60	2.55/4.50	3.84/4.20
3	CG	3.45/5.70	2.27/2.85	3.43/4.56
4	DG	2.91/3.90	3.13/3.15	2.98/5.85

Table 5 Calculation and measurement results of sheath currents in Cable No.4

Node	Grounding Mode	Calculation/Measurement (A)		
		I_A	I_B	I_C
1	DG	10.4/8.84	10.15/6.75	7.07/20.3
2	CG	9.45/5.33	7.22/9.91	11.05/20.3
3	CG	9.4/17.33	7.44/7.29	10.77/5.76
4	DG	18.7/20.1	18.72/18.3	17.8/14.81
5	CG	9.45/8.33	7.22/7.9	11.05/12.3
6	CG	9.4/5.31	7.44/5.71	10.77/16.2
7	DG	9.4/16.34	7.44/1.29	10.77/5.06

CONCLUSIONS

The calculation method of current flowing in the sheath of high-voltage XLPE single cable is introduced, which consists of capacitance part and induced part. There are many factors influencing the total sheath current. The capacitance current is determined by the structural parameters and length of cable, but is independent of the load of cable. The induced current is determined by the laying method of cable, the structure of cable and the load current, but is independent of the length of cable. Calculation methods and influencing factors are different for different grounding mode. In the case of both-end crossboned grounding, the dividing effect of resistance on capacitance current, and the effect of the ground resistance and the contact resistance at connection sites on induced current should be considered.

Acknowledgments

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