Calculation and Analysis of Circulating Currents in the Metal Sheath of XLPE Cables under Cross-Bonded Interconnection

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ABSTRACT

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| The large current of the grounding ring of the cable metal sheath not only increases electrical energy loss, but also affects the service life of the cable, and even causes major accidents such as cable line fires. Therefore, it is necessary to study the influencing factors of sheath circulation.The factors that generate metal sheath circulation mainly include the sheath circulation caused by the induced voltage generated by electromagnetic induction on the metal sheath due to the core current, and the leakage current injected into the metal sheath by electrostatic induction. This article establishes an equivalent model for calculating the circulating current of XLPE cable metal sheath based on cross interconnection, and writes a PyCharm program to verify the magnitude of the circulating current value of the three-phase sheath. A simulation model was built using PSCAD/EMTDC software, and the accuracy of the calculation method in this paper was verified by comparing theoretical values with simulation values. According to the debugging results, the larger the load current, the greater the loop current of the protective sheath. When the three equal lengths of cross shaped laying, three-phase load current balance, and cross interconnection are used, the minimum loop current of the protective sheath is achieved, while the grounding resistance of the circuit has almost no effect on the loop current. |

*Keywords: XLPE; induced current; leakage current; cross interconnection; influence factor*

1. INTRODUCTION

In power transmission systems, XLPE cables, as key components of transmission and distribution networks, are crucial for the safe and stable operation of the entire power system. Depending on their structure, XLPE power cables are divided into single-core and three-core cables. Single-core cables are typically used for voltage levels of 35 kV and above, while three-core cables are generally used for voltage levels below 35 kV. Taking single-core cables as an example, the structure from the outside to the inside includes the outer sheath, metal sheath, insulation shield, main insulation, conductor shield, and core. The metal sheath has four typical grounding methods: single-end grounding, double-end grounding, midpoint grounding, and cross interconnection grounding. In practical engineering cases, a combination of double-end direct grounding and intermediate cross interconnection grounding is generally adopted. [1–2]

During cable operation, circulating currents may be generated in the metal sheath. These circulating currents not only cause the metal sheath to overheat, affecting the normal operation of the cable and shortening its service life, but also increase the cable's operating impedance, leading to voltage fluctuations and current instability in the system, thereby affecting the stability of the power grid. The severity of circulating current issues and their potential impact on the performance of high-voltage cable systems have prompted in-depth research into their generation mechanisms, influencing factors, and control and optimization methods [12-15].

To calculate and analyze the circulating currents in XLPE cable metal sheaths, precise mathematical models and calculation methods are needed to predict the magnitude of circulating currents and their influencing factors. Analyzing the distribution characteristics and changing trends of circulating currents is significant for designing more efficient and safe cable systems. In-depth research on circulating currents can lead to the development of corresponding mitigation measures or optimization strategies, such as changing cable laying methods, using materials with specific electromagnetic properties, or adopting advanced current balancing technologies, thereby effectively reducing or eliminating the adverse effects of circulating currents.

2. Cross-Interconnected Metal Sheath Circulating Current Calculation Model

This paper uses XLPE cables at a voltage level of 110 kV as the research object. Generally, for XLPE cable lines over 500 m in length, the metal sheath is grounded at both ends directly, with cross interconnection in the middle. This study focuses on the general case where the three-phase metal sheaths are uniformly segmented, and each small segment of the cable is ≥500 m in length. The main reasons for the generation of circulating currents in the metal sheath include induced currents caused by electromagnetic induction and leakage currents caused by electrostatic induction.

**2.1 Calculation of Induced Current Components from Electromagnetic Induction**

According to the principles of electromagnetism, when alternating load currents flow through the cable cores, a time-varying magnetic field is generated around the cables, which links with the metal sheath and induces a voltage. Under ideal conditions, that is, with cross interconnection grounding, completely symmetrical three-phase loads, triangular cable laying, and equal lengths of the three cross-interconnected segments, the sum of the induced voltages would be zero. [3] No grounding circulating current would be generated when the metal sheath forms a closed loop with the ground. However, in practical engineering, cable laying is rarely perfectly symmetrical, and the lengths of the three cross-interconnected segments may not be exactly equal, so grounding circulating currents are inevitable.

On the other hand, when the metal sheath forms a loop with the ground and carries a circulating current, the circulating currents in the other two phases also induce voltages in the metal sheath of the phase in question. Therefore, the induced current from electromagnetic induction is caused by both the core current and the induced voltages from the circulating currents in the other phases. [4]

To calculate the circulating current caused by electromagnetic induction in the three cross-interconnected segments of the XLPE cable, a theoretical analysis of the cable sheath circulating current is conducted, and an equivalent circuit for a single cross-interconnected main segment of the cable metal sheath is established. To simplify the calculation, the distributed parameters in practical engineering are simplified to lumped parameters, and factors such as capacitive current are neglected. Figure 1 shows the equivalent circuit model of the cross-interconnected metal sheath.



**Fig. 1. Equivalent Circuit Model Diagram of Metal Sheath under Cross-Interconnection**

Write the three-phase metal sheath KVL equations:

where 、、 are the induced electromotive forces per unit length (1 m) in the metal sheath caused by the three-phase core currents; 、、 are the three-phase core load currents; 、、 are the circulating currents in the three-phase metal sheaths; 、、 are the induced voltages in phase A's metal sheath at positions one, two, and three of the cross interconnection due to the circulating currents in the other phases, with 、、 and 、、 defined accordingly; *Zu* is the self-impedance per unit length of the metal sheath; *L1、L2、L3* are the actual lengths of the three cross-interconnected segments; *Req* is the equivalent resistance of the grounding resistance at both ends of the metal sheath and the earth resistance for a distance L (taken as 1.5 Ω in this paper). [4–5]

According to Faraday's law of electromagnetic induction, the induced voltages caused by core currents and other phase circulating currents can be obtained as shown in equations (2) and (3):

In equations (2) and (3), *MA-a*, *MA-b*, *MA-c* are the mutual inductances per unit length between the core loop and the three-phase sheath loops when the core loop carries the load current. *MB-a, MB-b, MB-c* and *MC-a*, *MC-b,* *MC-c* are defined similarly. *Ma-b, Mb-c, Ma-c* are the mutual inductances between AB, BC, and AC phase metal sheaths, respectively. ω is the angular frequency under power frequency. [6]

Among them:

In equation (4) –(10), *rs* is the radius of the metal sheath; *rg* is the equivalent radius of the earth wire. In the formulas for self- and mutual inductance of the metal sheath, *rg* = *rs*. In the formula for mutual inductance between the core the and metal sheath, *rg* is taken as the core radius. *De* is the equivalent depth of the earth when the earth is used as the return path. *Dab* is the geometric center distance between phase A and phase B cables. *Dbc* is the geometric center distance between phase B and phase C cables. *Dac* is the geometric center distance between phase A and phase C cables. [7]

ρ is the earth resistivity, generally taken as 49.3 Ω·m, and f is 50 Hz.

In equation (12), *R* is the resistance per unit length of the metal sheath, and *L* is the self-inductance per unit length of the loop formed by the three-phase metal sheath and the earth.

Based on Lenz's law and Faraday's law of electromagnetic induction, the following is obtained:

By substituting equations (2)–(13) into equation (1) and solving for 、、 using the PyCharm software.

**2.2 Calculation of Leakage Current Components from Electrostatic Induction**

XLPE cables consist of three layers: core the, the insulation layer, and the metal sheath. Based on the cable structure, it can be equivalent to a cylindrical capacitor. There are also longitudinal currents flowing from the core through the main insulation to the metal sheath and from the metal sheath through the outer sheath to the ground, known as leakage currents. Leakage currents include capacitive and resistive components. Typically, the capacitive leakage current is of the same order of magnitude as the induced current in the sheath (several amperes), while the resistive leakage current is only in the milliampere range, much smaller than the capacitive leakage current. Therefore, only the capacitive leakage current is considered in the calculation, referred to below as leakage current.

Leakage current is influenced only by the cable operating voltage and the segment length. The principle diagram of leakage current is shown in Figure 2. *UA, UB UC*, are the voltages of the three-phase cores of the cable, i.e., the source voltages. *Z* is the equivalent impedance of the metal sheath. *R1, R2* are the grounding resistances at both ends of the sheath. *C* is the equivalent capacitance of the cylindrical capacitor. [8]

Since the insulation impedance of the cable is much greater than the equivalent impedance of the metal sheath and the cross-interconnection grounding resistance, the equivalent impedance of the metal sheath and the cross-interconnection grounding resistance are neglected. The capacitive reactance of the cable insulation is much greater than the impedance of the cross-interconnection grounding, so the voltage drop across the cross-interconnection grounding resistance is very small and is therefore ignored.



**Fig. 2. Schematic Diagram of Leakage Current Components**

The formula for calculating equivalent capacitance is:

In equation (14), *DC* is the diameter of the XLPE cable conductor. *D* is the thickness of the cable insulation. is the relative permittivity of the cable insulation material. In this study, the cable uses cross-linked polyethylene as its insulating material, with a relative permittivity of 2.3. *ε0* is the vacuum permittivity, with *ε0* = 8.86×10-12 F/m.

Taking the loop *A1-B2-C3* as an example to analyze leakage current, assuming uniform segmentation of the sheath into three parts and no faults, the leakage current in the circuit is：

Due to the balanced three-phase voltage of the system, the leakage current is equal to 0. When the sheath segments are 500 m/500 m/700 m in length, under 110 kV, the leakage current injected into the *A1-B2-C3* loop of the XLPE cable sheath is 1.47 A. [9]Calculations from Section 1.1 show that the sheath circulating current is generally between several amperes and several tens of amperes, with leakage current being relatively small.

Therefore, considering the leakage current component caused by electrostatic induction can improve the accuracy of the calculation, facilitating simulation verification.

3.Verification of Metal Sheath Circulating Current Calculation Examples

Combined with actual engineering cases, the magnitude of the metal sheath circulating current is generally related to factors such as three-phase load current, cross-interconnection segment length combinations, and cable laying methods. The following sections analyze the specific effects of these influencing factors. To verify the accuracy of the calculation method proposed in this paper, a simulation model is built using PSCAD/EMTDC software. Taking XLPE cables at 110 kV voltage level as an example for verification.

**3.1 Impact of Three-Phase Load Currents**

Under normal circumstances, 110 kV XLPE cables are laid in a triangular, isoceles right triangle, or horizontal configuration. Figures 3 and 4 illustrate the cable arrangement for different laying methods. Considering practical engineering scenarios, with a cross-interconnection segment length of 500 m/500 m/700 m as an example, the geometric center distance between phases is taken as 500 mm, and the three-phase load currents are balanced. Tables 1, 2, and 3 present the theoretical and simulation values of sheath circulating currents for different laying methods. [10]



**Fig. 3. Schematic diagram of the laying method of the cross shaped and isosceles right angled triangle**



**Fig. 4. Schematic diagram of horizontal laying method**

**Table 1 Theoretical and simulation values of sheath circulating current for triangular laying method**

|  |  |  |  |
| --- | --- | --- | --- |
| load current (A) | *Isa*(A) | *Isb*(A) | *Isc*(A) |
| theoretical value | Simulation value | theoretical value | Simulation value | theoretical value | Simulation value |
| 200 | 23.205 | 24.762 | 23.205 | 24.762 | 23.205 | 24.762 |
| 250 | 29.006 | 31.001 | 29.006 | 31.001 | 29.006 | 31.001 |
| 300 | 34.807 | 36.548 | 34.807 | 36.548 | 34.807 | 36.548 |
| 350 | 40.609 | 42.798 | 40.609 | 42.798 | 40.609 | 42.798 |
| 400 | 46.410 | 48.532 | 46.410 | 48.532 | 46.410 | 48.532 |

**Table 2 Theoretical and simulation values of sheath circulating current for horizontal laying method**

|  |  |  |  |
| --- | --- | --- | --- |
| load current (A) | *Isa*(A) | *Isb*(A) | *Isc*(A) |
| theoretical value | Simulation value | theoretical value | Simulation value | theoretical value | Simulation value |
| 200 | 25.087 | 25.777 | 25.943 | 26.520 | 19.106 | 19.995 |
| 250 | 31.359 | 32.692 | 32.429 | 33.826 | 23.882 | 24.739 |
| 300 | 37.631 | 38.602 | 38.914 | 40.091 | 28.659 | 29.587 |
| 350 | 43.902 | 45.010 | 45.400 | 47.102 | 33.435 | 34.526 |
| 400 | 50.174 | 52.511 | 51.886 | 53.991 | 38.212 | 40.872 |

**Table 3 Theoretical and simulation values of sheath circulating current for isoceles triangle laying method**

|  |  |  |  |
| --- | --- | --- | --- |
| load current (A) | *Isa*(A) | *Isb*(A) | *Isc*(A) |
| theoretical value | Simulation value | theoretical value | Simulation value | theoretical value | Simulation value |
| 200 | 24.167 | 25.413 | 24.576 | 25.738 | 21.055 | 21.921 |
| 250 | 30.209 | 31.577 | 30.720 | 32.090 | 26.318 | 27.555 |
| 300 | 36.251 | 37.889 | 36.864 | 38.582 | 31.582 | 33.331 |
| 350 | 42.293 | 44.544 | 43.008 | 45.120 | 36.846 | 38.231 |
| 400 | 48.334 | 50.033 | 49.152 | 51.057 | 42.109 | 43.891 |

It can be seen from Table 1,2,3 that the magnitude of the three-phase load currents and the cable laying method have a certain impact on the magnitude of the metal sheath circulating current. The greater the three-phase load current, the larger the sheath circulating current. Among the laying methods, the triangular method results in the smallest circulating current, while the horizontal method results in the largest. The circulating current of phases farther from phase A is smaller. Therefore, in engineering construction, the horizontal laying method should be avoided, and the triangular method should be adopted to effectively reduce the circulating current.

However, not all regions and environments are suitable for the triangular laying method. For example, in the Heihe section of the China-Russia DC back-to-back project, the area is covered by extensive permafrost. The triangular laying method is used to elevate the middle phase to avoid snowmelt water immersion. Additionally, the triangular configuration reserves space for thermal expansion. In the cable system at the Wenchang Satellite Launch Base in Hainan, where typhoons are frequent, a compact horizontal laying method is adopted to reduce interphase gaps, lower the center of gravity, and enhance wind stability. In the 110 kV line of Ningbo Petrochemical Park, where chemical pollution is severe, an inverted triangular laying method is used to lower the middle phase and prevent the accumulation of corrosive materials on top, facilitating the installation of fully sealed corrosion-resistant covers. Therefore, various actual environmental factors should be considered during cable laying. Table 4 presents the optimal cable arrangement methods and key technologies for different regions. [11]

**Table 4 Optimal cable arrangement methods and key technologies for different regions**

|  |  |  |  |
| --- | --- | --- | --- |
| types | Optimal arrangement method | Circulation control range | Core auxiliary measures |
| Coastal high corrosion | Unequal horizontal distance | 5%-10% | Cathodic protection+polyethylene anti-corrosion |
| permafrost region | Authentic Character Form | 3%-8% | HDPE anti frost expansion sleeve |
| Urban pipe gallery | Precision triangle | 4%-9% | Aluminum magnesium alloy shielding plate |
| typhoon zone | Tight level | 8%-12% | Double hinge windproof damper |
| chemical industry area | Inverted letter shape | 6%-11% | Nitrogen filled sealing cover |
| Underwater laying | Double triangle | 7%-13% | Redundant grounding system |

**3.2 Impact of Segment Length Uniformity**

When the three-phase load currents are balanced, with a load current of 300 A, using a triangular laying method with a phase-to-phase geometric center distance of 500 mm, and a segment length combination of 500 m/500 m/Xm. As *L3* varies, the circulating current values are analyzed. Table 5 presents the theoretical and simulation values of sheath circulating currents for different degrees of segment length uniformity. The uniformity of the segment length combination is the percentage ratio of the *L3* length to the *L1* length.

**Table 5 Theoretical and simulation values of sheath circulating current for different degrees of segment length uniformity**

|  |  |  |  |
| --- | --- | --- | --- |
| Uniformity of segment length | *Isa*(A) | *Isb*(A) | *Isc*(A) |
| theoretical value | Simulation value | theoretical value | Simulation value | theoretical value | Simulation value |
| 60% | 45.517 | 47.123 | 45.517 | 47.123 | 45.517 | 47.123 |
| 90% | 10.202 | 11.755 | 10.202 | 11.755 | 10.202 | 11.755 |
| 100% | 0 | 0.102 | 0 | 0.102 | 0 | 0.102 |
| 110% | 9.544 | 10.551 | 9.544 | 10.551 | 9.544 | 10.551 |
| 140% | 34.807 | 35.942 | 34.807 | 35.942 | 34.807 | 35.942 |

From Table 5, it can be seen that the less uniform the segment length combination, the larger the sheath circulating current. Therefore, in practical engineering, a more uniform three-segment cross interconnection length combination and triangular laying method should be adopted.

**3.3 Impact of Grounding Resistance in Different Laying Methods**

When the three-phase load currents are balanced, with a load current of 300 A, and an AB phase spacing of 500 mm, the impact of varying grounding resistance on sheath circulating current under different laying methods is shown in Table 6. The segment length combination is 500 m/500 m/700 m.

**Table 6 Sheath circulating current values with varying grounding resistance under different laying methods**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Laying method | Grounding resistance (Ω) | *Isa*(A) | *Isb*(A) | *Isc*(A) |
| T-shaped | 0.5 | 34.807 | 34.807 | 34.807 |
| 1.5 | 34.807 | 34.807 | 34.807 |
| 3 | 34.807 | 34.807 | 34.807 |
| isosceles right triangle | 0.5 | 36.299 | 36.622 | 31.809 |
| 1.5 | 36.251 | 36.864 | 31.582 |
| 3 | 36.377 | 36.924 | 31.363 |
| level | 0.5 | 37.772 | 38.451 | 29.110 |
| 1.5 | 37.631 | 38.914 | 28.659 |
| 3 | 37.860 | 39.000 | 28.224 |

As shown in Table 6, the grounding resistance has an extremely small impact on the metal sheath circulating current. Therefore, when seeking measures to suppress circulating currents, changing the grounding resistance should be excluded as a solution.

**3.4 Impact of Three-Phase Load Current Imbalance**

There are various reasons for three-phase load current imbalance, such as asymmetrical three-phase loads, unequal three-phase line impedances, mismatched or poorly operating three-phase transformer parameters, and grounding faults. Among these, single-phase short-circuit grounding faults have the most severe impact.

When *IA* = *IB* = 300 A, the load current imbalance refers to the absolute value of *IC* - *IA* expressed as a percentage of *IA*. Table 7 presents the theoretical and simulation values of the sum of the three-phase sheath circulating current amplitudes for cables under different degrees of load current imbalance. The cables are laid in a triangular configuration with a phase-to-phase center distance of 500 mm, and all segments are 500 m in length.

**Table 7 Theoretical and simulation values of sheath circulating current under different degrees of load current imbalance**

|  |  |
| --- | --- |
| Load current imbalance | *Is*(A) |
| theoretical value | Simulation value |
| 5% | 10.887 | 12.810 |
| 10% | 21.777 | 23.402 |
| 15% | 32.667 | 35.787 |
| 20% | 43.551 | 47.483 |
| 25% | 54.438 | 58.827 |

From the above table, it can be seen that the more severe the three-phase load current imbalance, the greater the circulating current, with an approximate proportional increase. Therefore, in practical engineering, three-phase load current imbalance should be avoided. Measures such as rational load distribution, optimized line design, and enhanced transformer maintenance should be implemented. In particular, during single-phase ground short-circuit faults, *Ik* becomes particularly large, leading to increased three-phase sheath circulating currents. Relay protection devices should promptly activate to identify and address fault causes to prevent insulation damage in XLPE cables due to overheating.

**4 Conclusion**

This paper focuses on the circulating current problem in cross-interconnected XLPE cable metal sheaths and delves into its calculation and analysis methods. By summarizing and analyzing existing circulating current calculation methods, the paper elaborates on the circulating current characteristics based on cross-interconnected structures and proposes an improved calculation model.

Firstly, by analyzing the principles of electromagnetic and electrostatic induction, the mechanism of circulating current generation in XLPE cable metal sheaths is explored, and an equivalent circuit model for cross-interconnected XLPE cable metal sheath circulating current is established. The calculation formulas for the three-phase sheath circulating currents *Isa*, *Isb*, and *Isc* are derived based on circuit principles. Subsequently, a simulation model is established, and extensive numerical simulations are conducted to thoroughly investigate the circulating current characteristics under various parameters. Using iterative methods, the effects of different laying methods, load currents, and segment length combinations on sheath circulating current are determined. By comparing with traditional methods, the effectiveness and accuracy of the improved model are verified. The research in this paper holds significant practical importance for enhancing cable engineering design quality, reducing circulating current risks, and ensuring the safe and reliable operation of cables.

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