Analysis and Calculation of Circulating Current in Grounding for Power Cables

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For the analysis of power cable line grounding circulation, we briefly introduced power cable metal sheath grounding mode and cable circulation analysis model in the first. Then, power cable support equations for calculating the circulation layer is derived. Combined with case analysis, different laying metal sheath of the induced voltage is calculated. The cable lines of the actual test results are similar to the calculation values, verifying the correctness of the analysis and calculation.

Keywords: Cable; Circulating Current; Metal Protective Layer; Crossover Interconnection.

1. Forewords

With the rapid development of Chinese economy and the city modernization level unceasing enhancement, the power cable developed rapidly as important equipment in city power grid. The power cable went through the development process of the oil filled cable and steel cable to XLPE cable. Compared with other cables, XLPE cable has many excellent performances. Such as, it is no need to supply oil and gas equipments, good fireproof performance, simple installation and maintenance. It has been adopted by more and more countries. The safe operation of power cable is related to the safety and reliability of city power grid, and it has been a high degree of attention throughout the world. Many times of cable line parallel operation of a plurality of in phase important parameters is closely related with the structure parameters of the power cable itself and its installation method, such as sheath current, current distribution, temperature field and carrying capacity.

1.1 Grounding Mode of Power Cable Metal Sheath

Usually it can achieve success under and in high voltage cable of joint and the end of metal protecting layer for different ways of ground treatment. According to the specific length of high voltage cable, it can set different access systems.
Generally, it has two ends connected directly, single ended protection connection and cross connection grounding.

Two Ends Connected Grounding Directly

Under normal circumstances, short distance of high voltage cable in two groups between the terminals used at both ends of the direct grounding way. It can lead to ground with special grounding grid directly grounding on both sides of the terminal metal protective layer. From Figure 1, we can see that directly grounded at both ends of the grounding system form a loop with the earth through the high voltage cable metal sheath. Because of the protective metal layer induced electromotive force, sheath formed ground circulation.

1.2 Single Ended Protection Grounding

This grounding mode is applied more widely. We often use it in combination with the high voltage cable lines between two terminals, two groups of joints or terminal and the joint. Besides, it also needs to lay a piece of reflux cable with path parallel. Single ended protection grounding system in this way by the end of the metal protecting layer is directly grounded and on the other end is grounded through the sheath protector, as shown in Figure 2. Under normal circumstances, the induction voltage on formation of voltage difference, and on metal sheath open does not connected to the current form in theory. But it is often due to the high voltage cable laying, installation, theft and other sectors, resulting in outer protective layer is damaged or the outer sheath insulation performance degradation. Consequently, it leads to the outer sheath grounding and the metal sheath grounding circulation.
1.3 Cross Connection Grounding

Cross connection grounding method generally used in high voltage cable which has long distance and three pieces of equal length. Three-phase metal sheath grounding ends of cross connection segment forms a unit system. A unit in the middle of two sets of joint metal sheath connected the ground through sheath protector after crossing the commutation. And on both sides of the two groups joint metal protecting layer is directly grounded. As shown in Figure 3. On the theory, induction voltage of cross connect method kept three-phase equilibrium through a metal shield. However, according to the actual environment of cable channel, it is more difficult to implement that the cable in three equal lengths. Even more, in the cable laying construction process is also very difficult to ensure that the effluent from the sheath injury, and there will be unequal, two or more ground conditions, resulting in high voltage cable metal sheath have large circulation.

![Figure 3. Metal sheath cross connection grounding system.](image)

1.4 Analysis Model and Calculation Method of Cable Circulation

According to the actual grounding status of power cable lines, the power cable has grounding currents, which mainly includes the grounding capacitive current and induced circulation. This article applies only to ground induced circulation is analyzed. Not only do power cable metal sheath exist induced electromotive force, but also metal sheath and cross protect interconnected grounding and the earth to form a loop. Therefore, metal sheath always flow circulation, and we call this circulation as metal sheath grounding circulation. When three-phase grounding imbalance caused by the cable fault, grounding mode, grounding defects and ground fault caused by metal sheath defects, the metal protective ring flow value will be significantly increased. The maximum can reach more than fifty percent of the main current of the wire core, reducing the load flow of power cable lines, and accelerate the aging of power cable main insulation of power cable lines.
Power cable metal sheath is mainly based on the length of cable line to select the grounding mode. No matter which way to choose, the equivalent circuit is the same. Specific equivalent circuit is shown in Figure 4. In Figure 4, $E_1$, $E_2$, $E_3$ respectively for induced electromotive force generated by the current through three-phase cable core on the A, B, C three-phase cable metal sheath; $E'_1$, $E'_2$, $E'_3$ respectively for induced electromotive force generated by the circulating current through three-phase cable core on the $I_{S1}$, $I_{S2}$, $I_{S3}$ three-phase cable metal sheath; $R_1$, $R_2$ for both ends of the cable sheath grounding resistance; $R_e$ for earth leakage resistance; $R$ for resistance of the cable metal sheath; $X$ for self inductance of the cable metal sheath resistance.

![Image of equivalent circuit](image)

Figure 4. Sheath circulation equivalent circuit.

Figure 4 shows the equivalent circuit, and supposes the length of the cable line is $L$, the voltage equation is:

\[
\begin{align*}
I_{S1}(R + jX) + (I_{S1} + I_{S2} + I_{S3})(R_1 + R_2 + R_e) + E'_1 &= E_1 \\
I_{S2}(R + jX) + (I_{S1} + I_{S2} + I_{S3})(R_1 + R_2 + R_e) + E'_2 &= E_2 \\
I_{S3}(R + jX) + (I_{S1} + I_{S2} + I_{S3})(R_1 + R_2 + R_e) + E'_3 &= E_3.
\end{align*}
\] (1)

Including: $R=R_sL$; $R_e=R_gL$; $R_g=0.0000493\Omega/m$; $X=2\omega L \ln(2D_e/D_s)$; $R_s$ as the resistance per unit length of cable sheath; $D_s$ for the loop equivalent depth when the cable sheath takes the earth as the circuit; $D_s$ as the diameter of the cable sheath.
1.5 The Cable is Laid in Parallel, and The Sheath is Desectorizing of Both Ends Connected to the Ground.

When the cable is desectorizing of both ends connected to the ground, the calculation method for each parameter in the formula (1) is:

\[
\begin{align*}
E'_1 &= I_{S2} \cdot jX_1L + I_{S3} \cdot jX_2L \\
E'_2 &= I_{S1} \cdot jX_1L + I_{S3} \cdot jX_1L \\
E'_3 &= I_{S1} \cdot jX_2L + I_{S2} \cdot jX_1L.
\end{align*}
\]  (2)

Including, \(X_1=2\omega \ln \left( \frac{D_e}{S} \right)\) is mutual inductance of the cable sheath of the phase and the side of the unit length; \(X_2=2\omega \ln \left( \frac{D_e}{2S} \right)\) is mutual inductance of the cable sheath of the side and side of the unit length; \(E_1=E_{S1}L, E_2=E_{S2}L, E_3=E_{S3}L\), \(E_{S1}, E_{S2}, E_{S3}\) respectively for unit length induced electric potential on three phase cable sheath.

If \(R_A=R_1+R_2+R_3, R_A=R_1+R_2+R_3,\) and let \(I_{S1r}, I_{S2r}, I_{S3r}\) as the real part of the sheath circulation; let \(I_{S1f}, I_{S2f}, I_{S3f}\) as the imaginary part of sheath circulation; let \(E_{1r}, E_{2r}, E_{3r}, E_{1f}, E_{2f}, E_{3f}\) respectively for the real and imaginary parts of inductive potential on three phase cable sheath. The matrix equation of the cable sheath circulation can be obtained according to the calculation rules of the complex number:

\[
\begin{bmatrix}
R_1 & R_y & R_y & -X & -X & -X_2 & -X_3 \\
R_y & R_y & R_y & -X_1 & -X & -X_1 & -X_1 \\
R_y & R_y & R_y & -X_2 & -X_1 & -X & -X_1 \\
X & X_1 & X_2 & R_y & R_y & R_y & R_y \\
X_1 & X & X_1 & R_y & R_y & R_y & R_y \\
X_2 & X_1 & X & R_y & R_y & R_y & R_y \\
\end{bmatrix}
\begin{bmatrix}
I_{S1r} \\
I_{S2r} \\
I_{S3r} \\
I_{S1f} \\
I_{S2f} \\
I_{S3f} \\
\end{bmatrix}
= \begin{bmatrix}
E_{1r} \\
E_{2r} \\
E_{3r} \\
E_{1f} \\
E_{2f} \\
E_{3f} \\
\end{bmatrix}
\]  (3)

1.6 The Cable is Laid in Parallel, and Sheath Cross Connect Ground

When the cable is connected to the ground, the length of the three cables is assumed to be \(L_1, L_2, L_3\) and \(L_1+L_2+L_3=L\). At this time, the parameters of the formula (1) are calculated as:
\[ E'_1 = I_{s2} \left( jX_1L_1 + jX_1L_2 + jX_1L_3 \right) + I_{s3} \left( jX_1L_1 + jX_1L_2 + jX_1L_3 \right) \]
\[ E'_2 = I_{s1} \left( jX_1L_2 + jX_1L_2 + jX_1L_3 \right) + I_{s3} \left( jX_1L_2 + jX_1L_2 + jX_1L_3 \right) \]
\[ E'_3 = I_{s1} \left( jX_2L_1 + jX_2L_2 + jX_2L_3 \right) + I_{s2} \left( jX_1L_1 + jX_1L_2 + jX_1L_3 \right) \]  \( \quad \text{(4)} \)

\[ \begin{align*}
E_1 &= E_{s1}L_1 + E_{s2}L_2 + E_{s3}L_3 \\
E_2 &= E_{s2}L_2 + E_{s3}L_3 \\
E_3 &= E_{s1}L_2 + E_{s2}L_3 \\
\end{align*} \]  \( \quad \text{(5)} \)

Let the above parameters into equation (1) derived cross connection matrix equation calculation of circulation in the cable sheath:

\[
\begin{bmatrix}
R_s & R_b & R_b & -X & -X_p & -X_q \\
R_b & R_s & R_b & -X'_s & -X'_p & -X_q \\
R_b & R_b & R_s & -X'_s & -X_p & -X_q \\
X & X_p & X_q & R_s & R_b & R_b \\
X_p & X & X_q & R_b & R_s & R_b \\
X_q & X_q & X & R_b & R_b & R_s
\end{bmatrix}
\begin{bmatrix}
I_{s1r} \\
I_{s2r} \\
I_{s3r} \\
I_{s1f} \\
I_{s2f} \\
I_{s3f}
\end{bmatrix}
= 
\begin{bmatrix}
E_{1r} \\
E_{2r} \\
E_{3r} \\
E_{1f} \\
E_{2f} \\
E_{3f}
\end{bmatrix}
\]  \( \quad \text{(6)} \)

Including:

\[
\begin{align*}
X_p &= X_1L_1 + X_1L_2 + X_1L_3 \\
X_q &= X_2L_1 + X_2L_2 + X_2L_3 \\
X'_p &= X_1L_1 + X_2L_2 + X_1L_3 \\
\end{align*} \]  \( \quad \text{(7)} \)

Grounding mode of two kinds of protective layer:

\[
\begin{align*}
E_{s1} &= 2\omega I \ln \left( \frac{\sqrt{3}}{2} \ln n + j \ln \frac{\sqrt{2}S}{GMR_g} \right) \\
E_{s2} &= 2\omega I \left( \frac{\sqrt{3}}{2} \ln \frac{mS}{GMR_g} - j \frac{1}{2} \ln \frac{S}{mGMR_g} \right) \\
E_{s3} &= 2\omega I \left( \frac{\sqrt{3}}{2} \ln \frac{mS}{GMR_g} - j \frac{1}{2} \ln \frac{n^2S}{mGMR_g} \right) \quad \text{(8)}
\end{align*} \]

Including, when cable is laid in parallel: \( m=1, \ n=2 \)
2. Case Analyses

In order to verify the accuracy of the analytic formula in the induction voltage of metal sheath and indicate the effect of running in the actual cable lines of metal sheath induced voltage, we used 110kv XLPE power cable which is used widely in current urban power grid as an example to illustrate.

In this paper, it takes the types of YJLQ02-1*1000mm² 110kV voltage class of XLPE power cable of single loop. Three-phase cable load current I=1000A, center of the cable axis distance s is 200mm, average diameter of cable metal sheath GMRS is 38.94mm, and consists of three root of single core XLPE power cable group into a three-phase circuit, as shown in Figure 5. We need to calculate for metal sheath of three-phase induction voltage under the parallel laying and equilateral triangle laying.

[1] When the three phase power cable is laid in a straight line

The induction voltage of A phase cable metal sheath is $E_{SA}$:

$$E_{SA} = 2 \times 50 \times 1000 \times 10^4 \left( \frac{\sqrt{3}}{2} \ln 2 \pm j \frac{1}{2} \ln \frac{2 \times 200^2}{38.94^2} \right) = 6002.8 + j19.83 \approx 20.717V/km$$

The induction voltage of B phase cable metal sheath is $E_{SB}$:

$$E_{SB} = 2 \times 50 \times 1000 \times 10^4 \left( \frac{\sqrt{3}}{2} \ln 200 \pm j \frac{1}{2} \ln \frac{200}{38.94} \right) = 14.17 - j8.181 \approx 14.19V/km$$

The induction voltage of C phase cable metal sheath is $E_{SC}$:

$$E_{SC} = 2 \times 50 \times 1000 \times 10^4 \left( \frac{\sqrt{3}}{2} \ln 200 \pm j \frac{1}{2} \ln \frac{4 \times 200}{38.94} \right) = -14.17 - j15.11 \approx 20.716V/km$$

When the three phase power cable is laid in an equilateral triangle

The induction voltage of A phase cable metal sheath is $E_{SA}$:
The induction voltage of B phase cable metal sheath is $E_{SB}$:

$$E_{SB} = 2 \times 50 \times 1000 \times 10^{-4} \left( \frac{\sqrt{3}}{2} \ln 1 + j \frac{1}{2} \ln \frac{200}{38.94} \right) = j16.36 \approx 16.36V / km$$

The induction voltage of C phase cable metal sheath is $E_{SC}$:

$$E_{SC} = 2 \times 50 \times 1000 \times 10^{-4} \left( \frac{\sqrt{3}}{2} \ln \frac{200}{38.94} - j \frac{1}{2} \ln \frac{200}{38.94} \right) = -14.17 - j8.18 \approx 16.36V / km$$

3. Conclusions

China started late in the technology of power cable, but foreign investment operation of 400 ~ 500 kV XLPE cables have been hundreds of KM. It is the development trend in the future that developing electric power cable new technology, improving the reliability and safety of the urban power grid, and reducing operating costs. We can regard the power cable metal sheath circulation changes as the power cable insulation condition judgment basis. At the same time, we also can accurately determine variation of circulation, and provide a reference to overrun alarm.

References


