Study on the ampacity of single-core submarine power cable with return conductor

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Abstract: In order to analyze the effect of internal Cu return conductor on ampacity, this paper establish three types of single core submarine power cable and calculate losses and thermal resistances. Results show that the internal return conductor can effectively reduce the cable loss, thereby increase the cable current carrying capacity. Cable with separated return conductor shows highest ampacity. When section area of return conductor increases, ampacity of cable improves correspondingly.

1. Introduction

High Voltage submarine cables are developing rapidly in China, moving toward higher voltage levels and higher transmission capacity. The submarine cable current carrying capacity is a key concern of submarine cable operation management. Due to lead sheath and armour layer directly grounded in the two ends, submarine cable has a significantly higher loss and lower ampacity than the land cable[1-3].

Adding a layer of return conductors to the single-core submarine cable can increase the current carrying capacity. Submarine cable with a return conductor layer was put into operation in China in 1987. Though, basic theoretical research on the up rating mechanism of the return conductor is still lacking.

This paper proposes a further analyzes of the influence of Cu return conductor layer on the ampacity of single core submarine cable. The results can provide reference for submarine cable selection and engineering construction design.

2. Methodology

Three types of single core submarine cable model are discussed, where type A without return conductor layer, type B with return conductor connected to the sheath layer, and type C with return conductor separated with the sheath layer. Without loss of generality, this paper aims mainly at submarine cable with magnetic armour structure and the dielectric loss of the cable is neglected.

2.1. Submarine cable model without return conductor

Figure 1 describes the electrical equivalent of single core submarine cable without return conductor layer (type A). The conductor temperature rise above the ambient temperature shall be obtained from the following formula (1):
2.2. Submarine cable model with return conductor connected to the sheath

Figure 2 describes the electrical equivalent of single core submarine cable without return conductor layer (type B). The conductor temperature rise above the ambient temperature shall be obtained from the following formula (2):

\[
\Delta \theta = I^2 R [T_1 + (1 + \lambda_1)T_2 + +(1 + \lambda_1 + \lambda_2)(T_3 + T_4)]
\]  

where, \(I\) is the current flowing in one conductor (A), \(R\) is the alternating current resistance of conductor at its maximum operating temperature (\(\Omega/m\)), \(\theta_c\) is the maximum operating temperature of conductor(K), \(\theta_m\) is the maximum operating temperature of cable sheath(K), \(\theta_s\) is the surface temperature of cable(K), \(\theta_{\text{amb}}\) is the ambient temperature(K), \(T_1\) is the thermal resistance per unit length between conductor and the sheath (K.m/W), \(T_2\) is the thermal resistance per unit length of the bedding between sheath and armour (K.m/W), \(T_3\) is the thermal resistance per unit length of the external serving (K.m/W), \(T_4\) is the thermal resistance per unit length between the cable surface and the surrounding medium (K.m/W), \(\lambda_1\) is the ratio of the total losses in metallic sheaths respectively to the total conductor losses, \(\lambda_2\) is the ratio of the total losses in metallic armour respectively to the total conductor losses.

2.3. Submarine cable model with return conductor separated with the sheath

Figure 3 describes the electrical equivalent of single core submarine cable without return conductor layer (type C). The conductor temperature rise above the ambient temperature shall be obtained from the following formula (3):

\[
\Delta \theta = I^2 R [T_1 + (1 + \lambda_{11} + \lambda_{12})T_2 + +(1 + \lambda_{11} + \lambda_{12} + \lambda_2)(T_3 + T_4)]
\]

where, \(\lambda_{11}\) is the ratio of the metallic losses respectively to the total conductor losses and \(\lambda_{12}\) is the ratio of the return conductor respectively to the total conductor losses.
Figure 3. Electrical equivalent of cable with return conductor layer separated with the sheath

\[
\Delta \theta = I^2 R[T_1 + (1 + \lambda_{11})T_{21} + (1 + \lambda_{11} + \lambda_{12})T_{22} + (1 + \lambda_{11} + \lambda_{12} + \lambda_2)(T_3 + T_4)]
\]  

(3)

where, \( T_{21} \) is the thermal resistance per unit length of the bedding between sheath and return conductor (K.m/W), \( T_{22} \) is the thermal resistance per unit length of the bedding between return conductor and armour (K.m/W).

2.4. Calculating method

For single core cable with the sheath and armour bonded together at both ends, the power loss is as follows:

\[
R_e = \frac{R_S R_A}{R_S + R_A} \\
\]

\[
R_S = \frac{R_t R_S}{R_t + R_S} \]  

(4)

where \( R_e \) is the equivalent resistance of sheath, return conductor and armour in parallel (\( \Omega/m \)), \( R_S \) is the resistance of sheath per unit length of cable at its maximum operating temperature (\( \Omega/m \)), \( R_A \) is the resistance of armour per unit length of cable at its maximum operating temperature (\( \Omega/m \)), \( R_t \) is the resistance of return conductor per unit length of cable at its maximum operating temperature (\( \Omega/m \)). \( \lambda_{11} \) and \( \lambda_{12} \) are given by:

\[
\lambda_{11} / \lambda_{12} = R_t / R_S
\]  

(5)

3. Analysis on influencing factors

3.1. The structure type of cable

The current carrying capacity of the cables of the three structures was calculated. Table 1 shows the calculation results. The cable used in the calculation has a conductor sectional area of 300 mm2, with a laying depth of 1.5 m. The ambient temperature is 15°C, and the thermal resistance coefficient of the surrounding soil is 0.9 K.m/W.

| Parameter     | Type A      | Type B      | Type C      |
|---------------|-------------|-------------|-------------|
| \( R_s \) (\( \Omega/m \)) | 3.41E-04    | 3.41E-04    | 3.41E-04    |
| \( R_t \) (\( \Omega/m \)) | -           | 6.65E-05    | 6.65E-05    |
| \( R_A \) (\( \Omega/m \)) | 9.95E-05    | 9.95E-05    | 9.95E-05    |
| \( \lambda_2 \) | 1.66        | 0.77        | 0.77        |
| \( \lambda_{11} \) | 1.66        | 0.126       | 0.126       |
| \( \lambda_{12} \) | 0           | 0.645       | 0.645       |
| \( T_2 \) (K.m/W) | 0.175       | 0.175       | 0.176       |
| Ampacity(A)   | 976         | 1031        | 1219        |

It can be seen from Table 1 that for cable with a Cu return conductor layer, the equivalent
resistance $R_\text{dc}$ decreases due to lower resistance of return conductor layer. As a result, cable of Type B and C significantly reduced loss and improved ampacity than cable of Type A.

While return conductor separated with sheath, the external diameter of cable increases, leading to a better heat dissipation. Therefore, type C cable shows higher ampacity than cable of type B.

### 3.2. The sectional area of return conductor

Ampacities of cables with different sectional area of return conductor are shown in Table 2. It can be seen from Table 2 that as the sectional area of return conductor increases, the loss factor of the lead sheath decreases and the ampacity increases. When the area is increased from 0 (no return conductor) to 500 mm$^2$, the loss factor of armour decreases from 1.7 to 0.5 by 66.4%, and the current carrying capacity increases from 900 A to 1300 A by 34.7%.

| Section area of return conductor (mm$^2$) | $\lambda_1$ | Ampacity (A) |
|----------------------------------------|-------------|--------------|
| 0                                      | 1.7         | 967          |
| 100                                    | 1.20        | 1080         |
| 200                                    | 0.94        | 1160         |
| 300                                    | 0.77        | 1219         |
| 400                                    | 0.65        | 1265         |
| 500                                    | 0.57        | 1303         |

### 4. Conclusion

Ampacities of submarine cables with different return conductor type were calculated and compared.

1. Due to lower resistance of Cu return conductor, submarine cable with return conductor layer obtains lower loss factor and higher ampacity than conventional submarine cable with magnetic armour structure. While return conductor separated with sheath, the external diameter of cable increases, leading to a better heat dissipation.

2. For cable with separated return conductor, as the sectional area of return conductor increases, the loss factor of the lead sheath decreases and the ampacity increases.

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