Life cycle cost assessment method considering multiple factors for economic evaluation of cable line steel brackets

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Abstract
In China, the bracket of underground high voltage cable transmission line is mainly made of various carbon steels. However, no unified standard exists for type selection of cable brackets in practice. Here, a selection method of the bracket based on life cycle cost assessment is proposed from the viewpoint of technical economy, in which the size of brackets, steel grade, carbon steel corrosion and eddy current loss are considered as influencing factors to the costs. Stress performance analysis under identical pole arm stress constraints is employed to determine the size and grade of carbon steel which influences the initial cost. And 3D coupled electromagnetic fluid-dynamical and thermal finite-element analysis is applied to calculate the eddy current loss of cable brackets which influences the operation cost. Meanwhile, multi-physics coupling analysis and experiment are conducted to prove the correctness of loss simulation calculation. Tafel curve measured by electrochemical corrosion experiment is used to obtain the corrosion rate of carbon steel which influences the maintenance cost by affecting service life of brackets. A case study is demonstrated, and the results show that the channel steel type is the most economical for the commendatory and the proposed method is effective.

1 INTRODUCTION

To greatly save space resources and improve the capacity of natural disasters, underground cable transmission systems are used in most urban power grids [1]. In China, there are three types of underground cable laying methods: direct burial, pipeline and tunnel. The laying method of the tunnel is shown in Figure 1.

The cable tunnel environment is humid and contains stray current, but the inside of the tunnel is a pollution-free gas environment. In China, the bracket of 110 kV and above underground high voltage cable transmission line is mainly made of carbon steel. The classical types of carbon steel are angle steel, channel steel and square steel, as shown in Figure 2. Generally, the designers choose the cable bracket for transmission line according to the requirements of the tunnel environment and the mechanical characteristics of cable brackets. However, the effects of eddy current loss and atmospheric corrosion on the steel bracket are not taken into account when the designer selects the cable bracket. In meeting the requirements of the tunnel environment and the mechanical characteristics of the cable line steel bracket, the cable line steel bracket was selected through the life cycle cost evaluation theory. Life cycle cost assessment has been widely used in power plant and transmission system [2, 3]. Life cycle cost theory is a comprehensive and systematic evaluation theory, which mainly researches the cost of equipment in the life cycle. Mendecka [4] applies a life cycle thermo-ecological cost approach to evaluate the environmental performance of wind turbines with different capacities and performance characteristics. Politano [5] considers the operating conditions and environment as the influencing factors of maintenance cost when establishing the life cycle cost model of controlled electrification of no-load power transformer. Amith [6] estimates the failure time of a wind turbine blade through a variety of factors, such as material, supply chain, manufacturing...
and operating conditions, in the life cycle cost analysis and optimization. The effects of various factors need to be considered when building a life-cycle cost model to make it more scientific and accurate.

In the existing literatures, Cui Houkun [7] proves that the cable steel bracket causes eddy current loss when adopting large section and large current cable, and the eddy current loss caused by angle steel, channel steel or square steel are different. The essence of atmospheric corrosion is the complex chemical reaction of metal covered with a thin liquid film. Tomashov [8] established an atmospheric corrosion model based on different liquid film thickness in 1964. The factors affecting atmospheric corrosion are not only the structure, composition and surface state of steel itself, but also the atmospheric composition, humidity and temperature. And stray current accelerated metal corrosion [9, 10]. For cable steel brackets, the size of the bracket, the type of steels, eddy current loss, stray current, ambient temperature of cable tunnel and relative humidity of atmosphere need to be taken as the influencing factors of the life cycle cost model.

In this paper a selection method of cable steel brackets based on life cycle cost assessment is proposed. This method takes the size of the bracket and the type of steel as the influencing factors that affect the initial investment cost. The stress performance analysis under identical pole arm stress constraints is employed to determine the size of steel brackets and the steel grade. The eddy current loss on the cable bracket is taken as the influencing factor of the operating cost. In order to obtain the eddy current loss and temperature distribution of cable brackets, a three-dimensional coupled electromagnetic hydrodynamics and thermal finite element analysis method was used. In order to verify the correctness of simulation calculation of multi-physical coupling model, the temperature rise experiment of cable brackets were carried out. The atmospheric corrosion rate of carbon steel is taken as the influencing factor of maintenance costs. In order to obtain the corrosion rate of carbon steel, Tafel curve (the curve drawn by the overpotential and the logarithm of the current density is called the Tafel curve) of carbon steel is measured by electrochemical corrosion test and data analysis is carried out. Finally, the life cycle cost assessment method is used to analyse and calculate the Feng-Luo transmission line.

The rest of this paper is organized as follows: In the second part, a life cycle cost assessment method for cable steel brackets selection is expounded. And in the third part, the temperature rise experiment of cable brackets is given to verify the correctness of the calculation method of multi-physical coupling field. In the fourth part, a specific calculation method for the cost of the steel bracket is given. Then the fifth part gives the case study. At last, the conclusion is demonstrated.

2 | LIFE CYCLE COST MODEL OF STEEL BRACKETS FOR CABLE LINE AND ITS EVALUATION METHOD

The evaluation processes of cable steel brackets are shown in Figure 3. Determine the size and steel grade of the steel bracket by applying the same load to the steel bracket of the cable line to meet the same stress characteristics as the constraint condition. Then the initial cost is obtained by the unit price of the selected carbon steel grade and the total mass of the bracket. The 3D coupled electromagnetic fluid-dynamical and thermal finite-element analysis is employed to calculate the eddy current loss of cable steel brackets and the temperature distribution inside the cable tunnel. Then calculate the operating cost from the eddy current loss on the cable steel bracket and the electricity price for industrial uses. Considering the influence of stray current, relative humidity of atmosphere and environmental temperature, the corrosion rate of carbon steel was measured by electrochemical corrosion experiments. The corrosion rate of carbon steel and the mechanical analysis of the cable steel bracket are combined for carrying out the service life of cable
steel brackets, which is used to estimate maintenance costs. The failure cost and the final scrap cost are obtained by looking up engineering cost. Finally, the life cycle cost of cable brackets can be computed.

2.1 Life cycle cost model of steel brackets for cable line

The life cycle cost assessment is to choose some alternatives with the most cost-effective approach to determine the lowest long-term cost of ownership. The life cycle cost model of cable steel brackets includes initial investment cost, operation cost, maintenance cost, failure cost and final scrap cost. The life cycle cost model is stated as follows [11, 12]:

\[
LCC = CI + \sum_{i=1}^{q} (CO_i + CM_i + CF_i) \frac{1}{(1 + i)^{t}} + \frac{CD}{(1 + i)^{t}}
\]  

(1)

Where, \(CI\) denotes the initial investment cost including equipment purchase cost, equipment transportation cost, and installation cost of cable brackets. \(CO\) denotes operation cost including eddy current loss cost. \(CM\) denotes the maintenance cost including overhaul cost of cable line in cable tunnel. \(CF\) denotes the cost of failure including equipment cost and labour cost required for replacement of damaged cable brackets. And \(q\) denotes the service life of cable line. \(i\) denotes the discount rate.

2.1.1 Initial cost analysis

The initial cost of cable steel brackets is influenced by the size of steel brackets and grade of steel. Therefore, it is necessary to determine steel grade and brackets size by structural mechanics calculation. Because the static load is loaded on the cable steel bracket, the structural mechanics calculation of the cable steel bracket needs to adopt the static theory. According to the theory of elastic-plastic mechanics, the stress field equation expressed in tensor form is described as follows [13, 14]:

\[
\begin{align*}
\sigma_{ij} + f_i &= 0 \\
\varepsilon_{ij} &= \frac{1}{2}(\alpha_{ij} + \alpha_{ji}) \\
\varepsilon_{ij} &= \frac{1 + \beta}{E} \sigma_{ij} - \frac{\beta}{E} \sigma_{kk} \delta_{ij} \\
\sigma_{ij} &= 2G \varepsilon_{ij} + \lambda \varepsilon_{kk} \delta_{ij} \\
P_i &= \sigma_{ij} n_j = \vec{P_i} \\
\alpha_i &= \vec{\alpha_i}
\end{align*}
\]

(2)

where \(\sigma_{ij}, f_i, \varepsilon_{ij}\) represent the stress (Pa), surface force (Pa), body force (Pa), and strain (m) of each element in the finite element, \(i,j,k\) are 1, 2, and 3 respectively, \(\alpha\) stands for displacement (m), \(\beta\) denotes Poisson ratio, \(E\) denotes young modulus, \(G\) is shear modulus, \(\delta_{ij}\) denotes the stress on a surface, and \(n_j\) denotes the direction cosine of the normal line outside the surface.

2.1.2 Operation cost analysis

The operation cost in the life cycle cost model only accounts for about 4% of the total cost, and the eddy current loss generated on the steel bracket of the cable line is much greater than the hysteresis loss and dielectric loss generated by it. Therefore, only the eddy current loss is used as the influencing factor of the initial cost of the cable line steel bracket.

The operation cost of the cable steel bracket is calculated based on the eddy current loss on the cable steel bracket and the electricity price for industrial uses. Therefore, the eddy current loss needs to be calculated by 3D electromagnetic analysis method. Cable steel brackets, metal hoops and cable cores generate eddy current, which is the eddy current regions \(\Omega_1\). Air and insulation materials are unable to produce eddy current, which is the non-eddy current regions \(\Omega_2\). Using Maxwell equations in which the magnetic vector potential and the electric scalar potential are introduced, the eddy current field equations are given as follows [15–17]:

Eddy current regions \(\Omega_1\):

\[
\nabla \times (\frac{1}{\mu} \nabla \times \vec{A}) - \nabla \left( \frac{1}{\mu} \nabla \cdot \vec{A} \right) + j\omega \vec{A} + \sigma \frac{\partial \vec{A}}{\partial t} = 0
\]

(3)

\[
\nabla \cdot \sigma (-j\omega \vec{A} - \nabla \varphi) = 0
\]

(4)

Non-eddy current regions \(\Omega_2\):

\[
\nabla \times \left( \frac{1}{\mu} \nabla \times \vec{A} \right) - \nabla \left( \frac{1}{\mu} \nabla \cdot \vec{A} \right) = j \vec{f}
\]

(5)

where \(j \vec{f}\) denotes the source density, \(\vec{A}\) denotes the vector magnetic potential, \(\varphi\) denotes the potential, \(\omega\) denotes the angular frequency changing in the magnetic field, \(\mu\) denotes the \(\varphi\) permeability, and \(\sigma\) denotes the electrical conductivity.

2.1.3 Maintenance cost analysis

The maintenance cost of the cable steel bracket is related to the replacement cycle of the cable bracket. The corrosion rate of carbon steel will affect the service life of the steel bracket. Therefore, the corrosion rate of carbon steel is one of the key factors that determine the service life of cable steel brackets. As the temperature rises, the corrosion rate of carbon steel is accelerated, which reduces the service life of the cable steel bracket. Therefore, the temperature distribution on the cable steel bracket is calculated by the 3D coupled fluid-dynamical and thermal finite-element analysis.

A cable tunnel is an enclosed space without forced ventilation. When the transmission line is running, the temperature difference caused by the heating of the cable and the cable bracket can cause airflow in the cable channel. For an incompressible ideal fluid, the steady-state flow equation of a 3D fluid
is as follows [18–20].

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$  \hspace{5em} (6)

$$\rho c \left( u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = k \nabla^2 T + Q$$  \hspace{5em} (7)

Where, \( u, v, \) and \( w \) are velocity components of fluid \( V \) in direction, m/s respectively. And \( \rho \) for fluid density, the unit for kg/m³, \( T \) denotes temperature in units of °C, \( k \) is the thermal conductivity, and the unit is W/(m⋅K). \( c \) is the heat capacity of air, the unit is J/(kg⋅°C), \( Q \) denotes heat flux, and the unit is W/m³.

The governing equation of convective heat transfer is as follows:

$$q = hS(T_w - T_e)$$  \hspace{5em} (8)

$$b = \frac{k \cdot Nu}{l}$$  \hspace{5em} (9)

where \( b \) denotes convection heat transfer coefficient, and the unit is W/(m²⋅K), \( S \) denotes acreage, and the unit is m², \( q \) denotes heat transfer over area \( S \) unit time, and the unit is W/m², \( T_w \) denotes cable tunnel concrete wall temperature, \( T_e \) denotes environment temperature, \( k \) denotes thermal conductivity, and the unit is W/(m⋅K), \( l \) denotes size, \( Nu \) denotes Nusselt number.

The heat radiated by the black body per unit time can be expressed by Stefan–Boltzmann law, the expression is as follows:

$$\Phi_0 = A \cdot M_0 \cdot T^4$$  \hspace{5em} (10)

where \( \Phi_0 \) denotes the heat flux of black body radiation, and the unit is W, \( T \) denotes the surface temperature, and the unit is K, \( M_0 \) denotes the black body radiation constant, which is taken as 5.67 \times 10^{-8} W/(m²⋅K⁴).

The radiant heat of objects other than black can be expressed by the modified form of Stefan–Boltzmann law, the expression is as follows:

$$\Phi = \gamma \cdot A \cdot M_0 \cdot T^4$$  \hspace{5em} (11)

where \( \gamma \) denotes the radiation blackness, which is less than 1.

3 | TEMPERATURE RISE TEST OF CABLE LINE STEEL BRACKETS

In order to verify the correctness of the calculation method of the electromagnetic field-fluid temperature field of the cable line steel bracket. The temperature rise experiment platform of the cable line steel bracket is built, and the temperature rise experiment is carried out on the cable line steel bracket. According to the relevant parameters of the experimental platform, the finite element model is established and calculated. Then compare the experimentally measured temperature data with the finite element simulation calculation results to verify the correctness of the calculation method of the electromagnetic field-fluid temperature field of the steel wire bracket of the cable line.

3.1 | Temperature rise test of cable line steel brackets

The temperature rise test platform of cable brackets is shown in Figure 4. The platform adopts single-phase cable, the cable type is YJLW03 64/110 kV and the cable is placed directly above the bracket of the lowest cross arm, as shown in Figure 5. The control platform in the experimental platform is used to adjust the current in the cable circuit and monitor the experimental data. The temperature of each point is measured through the thermocouple module. The ambient temperature is marked as \( T_0 \). The cross-arm temperature of the underlying bracket is marked as \( T_1 \). The temperature of the second bracket crossbar is marked as \( T_2 \). The core temperature of cable is marked as \( T_3 \).
To reduce the influence of experimental error on the experimental results, the current value flowing through the cable in the temperature rise experiment of the cable bracket is set to be 1000 A. After 6 h, the temperature of each temperature measuring point tends to be stable. The temperature of each time point is recorded as shown in Figure 6. The final ambient temperature $T_0$ is 39.30 °C, the cable bracket $T_1$ is 50.05 °C, the cable bracket $T_2$ is 47.70 °C, and the cable core temperature $T_3$ is 74.30 °C.

### 3.2 Temperature simulation calculation

A 3D calculation model is built based on the cable bracket temperature rise test platform. Tables 1 and 3 show the geometric properties of the model. Tables 2 and 4 show the material properties of the model.

The steel models selected for the cable line steel bracket are mainly Q235 carbon steel and Q345 carbon steel. The relative permeability of these two types of carbon steel is 200–300. Some scholars set the relative permeability to be 200 when performing electromagnetic field simulation calculations on the steel bracket of the cable line [7]. Therefore, in the electromagnetic field analysis of the steel bracket of the cable line, the relative permeability of the steel bracket is set to be 200.

The electromagnetic field analysis of the steel bracket of the cable line adopts the time-harmonic magnetic field solver, and specifically selects the ANSYS time-harmonic magnetic field module. And the cable core is loaded with a sinusoidal alternating current with a frequency of 50 Hz and an effective value of 1000 A. Then the boundary conditions are set on the surface boundary of the outside air so that the lines of magnetic force are parallel, and the vector magnetic potential are $A_x = 0$, $A_y = 0$, $A_z = 0$. The fluid temperature field analysis of the cable line steel bracket adopts a 3D flow field unit to solve the temperature field and the flow field. The model is still the calculation model in the electromagnetic field, and the division remains unchanged, so that the two fields have a one-to-one correspondence. When analyzing the fluid field of the cable line steel bracket, the indirect coupling method is adopted. That is, the Joule heat calculated by the electromagnetic field is loaded into the flow field and temperature field calculation through the indirect coupling method. The ambient temperature is set to be 39.3 °C, and the air gap surface is a non-slip boundary condition. That is, $v_x = v_y = v_z = 0$, and the reference pressure is set. The temperature distribution of the bracket and cable is shown in Figure 7.

In Table 5, the error of temperature $T_1$ is 2.72%, the error of temperature $T_2$ is 1.72%, and the error of temperature $T_3$ is 2.46%. In the allowable range of error, the calculation method of temperature rise is reasonable and correct.
TABLE 2 Material parameters for calculate electromagnetic fields

| Part                     | Resistivity (Ω·m) | Relative permeability |
|--------------------------|-------------------|-----------------------|
| Conductor                | 1.75 × 10^{-8}    | 1                     |
| Semi-conductive tape     | –                 | 1                     |
| Conductor screen         | –                 | 1                     |
| XLPE insulation          | –                 | 1                     |
| Insulation screen        | –                 | 1                     |
| Semi-conductive buffer   | –                 | 1                     |
| water-blocking layer     | –                 | 1                     |
| Corrugated aluminum sheath | 2.83 × 10^{-8}    | 1                     |
| Retardant PVC sheath     | –                 | 1                     |
| Steel brackets           | 2 × 10^{-7}       | 200                   |
| Air                      | –                 | 1                     |

TABLE 3 Geometric parameters of cable model

| Cable structure         | YJLW03 64/110 kV | YJLW02 127/220 kV |
|-------------------------|------------------|-------------------|
|                         | Thickness (mm)   | External diameter (mm) |
| Conductor               | 19.5             | 39                 |
| Semi-conductive tape    | 0.8              | 40.6               |
| Conductor screen        | 1.5              | 43.6               |
| XLPE insulation         | 16               | 75.6               |
| Insulation screen       | 1                | 77.6               |
| Semi-conductive buffer  | 5                | 87.6               |
| water-blocking layer    | 2.3              | 92.6               |
| Corrugated aluminum sheath | 4.5            | 101.2              |
| Retardant PVC sheath    | 4.5              | 101.2              |

TABLE 4 Material parameters for fluid temperature field calculation

| Part                     | Thermal conductivity (W/(m·K)) | Density (kg/m³) | Specific heat capacity (J/(kg·K)) |
|--------------------------|---------------------------------|-----------------|----------------------------------|
| Conductor                | 398                             | 8933            | 385                              |
| Semi-conductive tape     | 0.3                             | 1150            | 1960                             |
| Conductor screen         | 0.2                             | 938             | 1670                             |
| XLPE insulation          | 0.27                            | 920             | 2500                             |
| Insulation screen        | 0.2                             | 938             | 1670                             |
| Semi-conductive buffer   | 0.22                            | 910             | 1883                             |
| water-blocking layer     |                                 |                 |                                   |
| Corrugated aluminum sheath | 237                            | 2700            | 880                              |
| Retardant PVC sheath     | 0.16                            | 1380            | 1283                             |
| Steel brackets           | 493                             | 7850            | 460                              |
| Air                      | 0.025                           | 1.16            | 1000                             |

FIGURE 7 Temperature distribution of steel bracket and cable. (a) Temperature distribution of cable line brackets, (b) cable temperature distribution

| Measured point | Simulation result | Experimental result | Error  |
|----------------|-------------------|---------------------|--------|
| T₁             | 49.03°C           | 50.40°C             | 2.72%  |
| T₂             | 48.52°C           | 47.70°C             | 1.72%  |
| T₃             | 72.47°C           | 74.30°C             | 2.46%  |

4 | LIFE CYCLE COST CALCULATION OF STEEL BRACKETS FOR CABLE LINE

In this section, the calculation method of initial cost, operating cost and maintenance cost of the steel cable bracket are demonstrated separately considering the effective factors. At last, the cost of each part is brought into the life-cycle cost model to calculate the life-cycle cost of the steel cable bracket.

4.1 | Initial cost calculation based on mechanical analysis of cable line steel brackets structure

The steel grade and size of the steel bracket are determined through structural mechanics calculations, and then the cost of a single bracket is obtained by combining the steel price and processing costs. The geometric parameters of steel supports and concrete walls are shown in Table 1. The gravity of the cable and the hoop is applied as a load on the contact surface between the hoop and the bracket, and a fixed displacement constraint is set on the column.

The stress distributions of steel brackets were calculated by structural mechanics simulation. The maximum stress of the angle steel bracket is 247 MPa. The maximum stress of the channel steel bracket is 248 MPa. And the maximum stress of the square steel bracket is 148 MPa. Therefore, for different types of steel brackets, different grades of carbon steel need to be selected. The yield strength of Q235 carbon steel is 235 MPa. The yield strength of Q345 carbon steel is 345 MPa. In order to prevent the cable steel bracket from being destroyed by static force, the angle steel bracket and the channel steel bracket adopt...
Q345 carbon steel, and the square steel bracket adopts Q235 carbon steel. The unit price of different types of steel brackets is in Table 6.

Under the influence of atmospheric corrosion, with the increase of the service life of the cable bracket, the thickness of the cross arm of the cable bracket will become thinner, which will cause the bearing capacity of the cable steel bracket to decrease. In order to prevent the transmission line failure caused by the damage of the cable bracket, the cable steel bracket needs to be replaced. When the thickness of the angle steel bracket cross-arm is 6.5 mm, the maximum stress of the stent is 327 MPa. When the thickness of the channel steel bracket is 5.9 mm, the maximum stress of the channel steel bracket is 328 MPa. And when the thickness of the square bracket is 4 mm, the maximum stress of the square steel bracket is 224 MPa. At this time, the yield strength of carbon steel has reached 95%. To prevent transmission line failure due to damage to the cable bracket, the cable steel bracket needs to be replaced.

### 4.2 Operation cost calculation based on electromagnetic field analysis of cable line steel brackets

Eddy current loss is a key factor in operation cost. The eddy current loss on the steel bracket is calculated with a three-dimensional electromagnetic field simulation. According to the cable tunnel of Feng-Luo transmission line, the simulation model is established. The cable type is YJLW02 127/220 kV. The geometric parameters of the model are listed in Tables 1 and 3. Table 2 shows the material properties of the model. The 3D simulation model includes cable line steel brackets, three-phase cables, hoops and fluid air in tunnel.

According to the state grid, the current flowing in the cable under the actual working condition of Feng-Luo transmission line is 500 A, so 500 A sinusoidal alternating current is applied during the electromagnetic field simulation calculation of the cable line steel bracket.

The time-harmonic magnetic field solver is used to analyse the electromagnetic field of the cable steel bracket, the current effective value of the cable core is 500 A and the current frequency is 50 Hz. And the phases of loading current of the three cables is 0°, 120°, and −120°, respectively. Then the boundary conditions are set on the surface boundary of the outside air so that the lines of magnetic force are parallel, and the vector magnetic potential is \( A_x = 0, A_y = 0, A_z = 0 \). The current density distribution of the cable steel bracket is obtained by electromagnetic field analysis as shown in Figure 8. The eddy current loss of angle steel brackets, channel steel brackets and square steel brackets are 0.675, 1.15 and 0.994 W, respectively. And the electricity price for industrial uses in Wuhan city is 0.945 CNY per kilowatt, the annual eddy current loss cost of a single cable steel bracket is calculated as shown in Table 7.

### 4.3 Maintenance cost calculation based on electrochemical corrosion analysis

Replacing the cable steel bracket during the service life of cable transmission line increases maintenance costs. Therefore, the service life of the cable steel bracket needs to be analysed for the calculation of the increased maintenance costs due to the replacement of the steel bracket. And the rate of carbon steel is a key factor in determining the service life of steel brackets. The effects of stray current, relative atmospheric humidity and ambient temperature need to be considered here, and then the corrosion rate of carbon steel is obtained through electrochemical corrosion experiments. Finally, combined with the corrosion rate of carbon steel and the mechanical analysis of the cable steel bracket, the service life of the cable steel bracket was calculated.

#### 4.3.1 Calculation of fluid-temperature field of steel brackets for cable line

The fluid temperature field analysis of the cable line steel bracket adopts a three-dimensional flow field unit to calculate the temperature field and the flow field. The model is used as the calculation model in the electromagnetic field, and the division remains unchanged, so that the two fields have a one-to-one correspondence. When analyzing the fluid field of the
cable line steel bracket, the indirect coupling method is adopted. That is, the Joule heat calculated by the electromagnetic field is loaded into the flow field and temperature field calculation through the indirect coupling method. The ambient temperature is set to be 39.3°C, and the air gap surface is a non-slip boundary condition. That is, \( v_x = v_y = v_z = 0 \), and the reference pressure is set. The calculation results are shown in Figure 9. The maximum temperature of the angle bracket, the channel bracket and the square bracket are 19.93, 20.07, and 20.13°C.

4.3.2 Electrochemical corrosion experiment

The electrochemical corrosion experiment flow chart is shown in Figure 10. In the environment of 95% ± 3% relative humidity and 20°C, thin liquid film measuring device is used to measure the thickness of liquid film. And the open circuit potential and the Tafel curve of the carbon steel reaction surface are measured at an ambient temperature of 20°C, a 500 A AC load on the cable, and a 0.35% NaCl solution with a liquid film thickness of 0.1 ± 0.03 mm. Finally, the corrosion rate of carbon steel in cable tunnel under special atmospheric environment is calculated by Faraday’s law.

The liquid film measuring device consists of a humidifier, a power switch, a resistance, a vertical micrometer, a self-made electrolytic cell, a base, a multimeter, a DC power supply and a temperature and humidity detector, as shown in Figure 11(a). The principle diagram of thin liquid film measuring device is shown in Figure 11(b). Before measuring the thickness of the liquid film, the stainless steel probe is adjusted and positioned directly above the electrode. At this point, the ammeter reading is zero. The driving probe descends gradually until the probe touches the surface of the liquid film. The ammeter displays a certain current value and records the reading as 1 on the micrometer. Continue driving the probe downward until the ammeter value suddenly increases, indicating that the probe has touched the surface of the metal electrode, and the micrometer records the reading of 2. The liquid film thickness is the difference between reading 1 and reading 2.

The thin liquid film electrolyser is shown in Figure 12. The unique structure of the device ensures that the thin liquid film formed is evenly distributed on the surface of the working electrode. The columnar steel electrode with a diameter of 5 mm and a height of 20 mm is processed to form a working electrode system, which is placed in the electrolytic cell. The upper surface is exposed as a working surface. The auxiliary electrode Pt ring is placed at the position shown in Figure 12. The working electrode is placed at the centre of the Pt ring and the reference electrode is placed near the working electrode.

With the thin liquid film measuring device shown in Figure 12, the thickness of the liquid film formed on the surface of carbon steel is measured in the environment of temperature 20°C and relative humidity 95% ± 3%. The thickness of liquid film measured by thin film measuring device is shown in Table 8.
TABLE 8 Thickness of liquid film formed after 2 h

| Liquid film thickness (mm) | 1   | 2   | 3   | 4   | Average value |
|----------------------------|-----|-----|-----|-----|---------------|
|                            | 0.098 | 0.104 | 0.126 | 0.084 | 0.103 |

The open circuit potential and Tafel curve of carbon steel are measured by thin liquid film electrochemical experiment platform.

1. Open circuit potential

The open circuit potential of carbon measured by CHI608C electrochemical analyser in 0.35% NaCl thin liquid film with ambient temperature of 20°C, liquid film thickness of 0.103 ± 0.05 mm. And the load of the cable is 500 A AC. The OCP change test results are shown as Figure 13.

1. Tafel curve test

Tafel curves of samples in NaCl aqueous solution are measured by CHI608C electrochemical analyser. The measured Tafel curve is shown as Figure 14.

At the equilibrium potential ±60–120 mV, it is a linear polarization region. The data of polarization region are linearly fitted to get two line segments, and the longitudinal coordinate of the intersection point of the line segments is corrosion current. Divide the corrosion current by the exact area of the test electrode, then the corrosion current density is 10.206 μA/cm².

The corrosion rate of metals is expressed by corrosion weightlessness or corrosion depth, or by corrosion current density. They are converted by Faraday’s law:

$$ v = \frac{M}{nF} \frac{i_{cor}}{\rho} = 3.73 \times 10^{-4} \frac{M}{n} i_{cor} (g/m^2h) \quad (12) $$

$$ d = \frac{v}{\rho} = 3.28 \times 10^{-3} \frac{M}{n} i_{cor} (mm/a) \quad (13) $$

where, $v$ denotes corrosion rate (g/m²h), $d$ denotes corrosion depth (mm/a), $i_{cor}$ denotes corrosion current density (μA/cm²), $M$ denotes gram atomic weight (g), $n$ denotes atomic value of metal, $F$ denotes Faraday constant, and $\rho$ denotes density of metal (g/cm³).

For Q235 carbon steel, $M = 56$ g, $n = 2$ and $\rho = 7.8$ g/cm³, the corrosion rate of Q235 carbon steel is calculated to be 0.1202 mm/a by Equation (11). When the thickness of the cross arm of the angle steel bracket is 6.5 mm, the maximum stress of the cable steel bracket has reached 95% of the yield strength of Q345 carbon steel. The cable steel bracket needs to be replaced. Because the corrosion rate of Q235 and Q345 is basically the same, the replacement period of the angle steel bracket is 12 years. The replacement intervals of the channel steel bracket and the square steel bracket are 17 and 8 years, respectively.

5 | ECONOMIC EVALUATION OF THREE TYPES OF STEEL BRACKETS FOR FENG-LUO 220 KV TRANSMISSION LINE

5.1 | Life cycle cost calculation of steel brackets for Feng-Luo transmission line

According to the data provided by the State Grid Corporation of China, the length of the Feng-Luo transmission line is 1.32 km, and the total number of the bracket is 420. When the service life of the transmission line is 30 years, the full life cycle cost of the angle bracket is calculated.

In this line, the budget cost of cable brackets equipment is $400 \times 420 = 168,000$ CNY, the equipment transportation cost is 1,800 CNY, the installation cost is 126,000 CNY, and the CI is 295,800 CNY. The average power loss on a single bracket calculated according to the electromagnetic field is 0.675 w, and the electricity price for industrial uses in Wuhan city is 0.945 CNY/KWH. So the CO is 2,350 CNY. The frequency of maintenance is once a year and the cost of maintenance is 10,200 CNY. According to the corrosion analysis and the calculation of carbon steel, the cable bracket is required to be replaced in the 13th and 25th years, $CM_{13} = 1800 + 126000 + 0.04 \times 420 + 107000 = 402,800$ CNY, $CM_{25} = 402,800$ CNY. CF is the failure cost, the failure rate of cable line bracket is 5 every year, each bracket costs 400 CNY, a single replacement labour costs 900 CNY, then $CF = 5 \times 400 + 900 = 2,900$ CNY. CD is the waste cost, including 126,000 CNY of labour cost, 18,800 CNY of transportation cost and 20,800 CNY of charges for decomposing the bracket, so $CD = 126000 + 1800 – 20800 = 107,000$ CNY.
Wherever possible, the monetary value of benefits and costs should change over time. This requires choosing a discount rate, which determines the value of future costs and benefits relative to current costs and benefits. The calculation method of the discount rate is the social average rate of return method. The influencing factors of discount rate include capital markets, investment risks, and inflation [21].

Substitute the cost of each part into Equation (1), where \( i \) is the discount rate in case of currency depreciation, and I take 0.04 [22]. When the service life of the cable line is 30 years, the full life cycle cost of the angle steel bracket is 976,100 CNY. When channel steel or square steel cable line steel brackets are selected, they life cycle cost are 880,900 and 1,258,400 CNY respectively. The detailed cost of different forms of steel brackets is shown in Table 9.

| Angle steel brackets | Channel steel brackets | Square steel brackets |
|----------------------|------------------------|-----------------------|
| CI(CNY)              | 295,800                | 333,600               |
| CO(CNY)              | 40,600                 | 69,200                |
| CM(CNY)              | 559,400                | 388,800               |
| CF(CNY)              | 47,300                 | 56,300                |
| CD(CNY)              | 33,000                 | 33,000                |
| LCC(CNY)             | 976,100                | 880,900               |

5.2 Life cycle cost analysis of steel brackets for Feng-Luo transmission line

By comparing the costs of various parts of cable brackets Feng-Luo, the initial cost and operation cost of angle steel brackets are the lowest, the maintenance cost of the channel steel bracket is the lowest, and the failure cost of the square steel bracket is the lowest. Channel steel brackets cost the least considering the life cycle cost of Feng-Luo transmission line. Therefore, it is recommended to use channel steel brackets for 220 kV Feng-Luo transmission line.

6 CONCLUSION

In this paper, a selection method of the bracket based on life cycle cost assessment is proposed from the viewpoint of technical economy, in which the size of brackets and steel grade, carbon steel corrosion and eddy current loss are considered as influencing factors to the costs. Under the premise that the current flowing through the transmission line cable is 500 A, the environment of 95% ± 3% relative humidity and 18 °C, and the discount rate in the case of currency depreciation is 0.04. The life cycle cost of angle, channel, and square brackets are calculated. Through the life cycle cost comparison of three kinds of steel brackets, it is concluded that channel steel brackets are the most economical.

The proposed method provides quantifiable technical and economic indicators for cable line designers in the selection design of cable line brackets.

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