Research on the Real-time Calculation Model for Transient Temperature Rise of Duct-Laid Cable

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\textbf{Abstract.} This paper presents a thermal circuit model for analysis of transient temperature rise of duct-laid single cable and its application in practical analysis. The sample data was obtained by general computation software. The parameters of the model was extracted through these sample data based on genetic algorithm. The sample data of the general computation software were employed to verify the validity of the model. The maximum error of temperature rise was observed to be less than 3K. Both the model structure and the parameter extraction method were confirmed to be effective and reliable through the verification test. Application of test data for model parameter extraction may avoid the influence of complicated environment conditions on accuracy of numerical simulation and improve the adaptability of the model in practical application. In addition, the study showed that flexible adjustment of the model may meet the requirements for analysis of transient temperature rise at various parts of the cable while maintaining the convenience and accuracy of the model.

1. Introduction

With the development of the city and the demand of the city beauty, more and more power cables were used in the city power grid. The power operator pay more attention to how to manage the power cables and increases the utilization ratio of power cables. In the urban, direct burial and duct are the main laying mode of underground power cables. Because the distance between nearby ducts is small and the heat interaction is obvious, the designed current rating of duct power cables is conservative. In recent time, the city developed with a high speed and the demand of power increased very fast too. The load in some power cable lines has approached to the designed value. This brought some pressure to keep the safety and reliability of power. How to evaluate the real-time temperature of cable core accurately and quickly and improve the utilization ratio of power cables has became the focus problem for power operators\textsuperscript{[1]}.

There are two main methods to obtain the temperature of power cable core. The indirect measurement method is the fiber optic measurement system. The fiber optic is installed on the surface of power cable or between the sheath and insulation. The cable core temperature could be calculated by thermal circuit\textsuperscript{[2-4]}. The result depends on the health of measurement system. The error of detect result and information transmission bring hesitation for power operator to manage the load of the cable.
Otherwise, there are many old cable line without fiber optical measurement. Calculation methods include experience formula and numerical method. Experience method is always used to calculated the steady-state temperature rise\(^5,6\). Because of the good adaptable, numerical method was developed rapidly in recent years\(^7\text{-}14\). Because the multiple loop underground power cables are laying in a same section and the solution domain is divided into many small unit, the calculation time of numerical method is long, especially for duct power cables. It is not reality to obtain the real-time cable core temperature by numerical method. Therefore, it is necessary to find a rapid method to calculate the transient temperature rise of power cables in duct.

A thermal circuit model based on centralized parameters was provided to improve the calculation efficiency of single power cable in duct and meet the demand of real-time analysis. The transient temperature of cable core and sheath could be acquired rapidly by this model.

In order to overcome the problem that the Foley Leaf number and Bilbo number representing the heat transfer dynamic character from cable to environment can not fit the centralized parameters, a balance thermal resistance and a balance thermal inductor were used in the model to simulate the time varying character of thermal resistance and thermal capacity during the heat transfer process. This model doesn’t depend on the detect surface temperature. The model is actually simple and rapidly. The feasibility and effectiveness of this model were proved by simulation example and trial.

2. Transient thermal model

The temperature of cable core depend on the loss in cable and thermal parameter of cable and environment. The loss in cable have been studied by many researchers and the result was used widely in actual. The thermal parameters depend on the structure of cable and environment. According to the previous study, the duct can be included in the outer thermal parameter with environment. When the environment temperature is set as the reference point, the transient thermal model is shown in Figure 1.

![Figure 1. Transient thermal circuit model with lumped parameter for duct-laid cable.](image)

Qc is the cable core loss. Qd is the dielectric loss. Qs is the eddy current loss in sheath. C1 is the thermal capacity between the cable core and sheath. C2 is the thermal capacity of out cove of cable. C3 is the environment thermal capacity. R1 is the thermal resistance between the cable core and sheath. R2 is a balance thermal resistance. R3 is the thermal resistance of outer cover of cable. L1 is the balance inductor of environment. Here, the balance thermal resistance R2 and balance thermal inductor L1 are used to overcome the problem that the Foley Leaf number and Bilbo number representing the heat transfer dynamic character from cable to environment can not fit the centralized parameters. These two parameters should fit the equation \(R2*C3 = L1/R3\).

The transient model in Figure 1 doesn’t depend on the loss and current. The parameters are only relative with the thermal characteristic of duct, soil, cable, and so on. When the model is confirmed, the model can be used to calculated the cable core temperature under different current load and give out satisfied result. The reference temperature of this model is environment temperature. It is no necessary to install temperature monitoring system to detect the surface temperature of power cable. This model is easy and feasible.

3. Simulation example and verification

3.1. Model construction
In order to get the heat transfer rules, a duct example was constructed by CYMCAP. The duct mode was shown in Figure 2. The cable laying in the first hole was a 10kV three core power cables as shown in Figure 3. There are 4*3 pipes in duct. The length is 1.3m and the height is 1.1m. The inner diameter of the hole is 150mm. The top of duct is 1.5m deep under the ground surface. The thermal parameters were shown in Table 1.

![Figure 2. Calculate model in CYMCAP.](image)

![Figure 3. Cross-section of the cable.](image)

### Table 1. Thermal parameters

| Materials | Thermal resistivity (K·m/W) | Density (kg/m³) | Specific Heat (J/ (kg·K)) |
|-----------|-----------------------------|-----------------|--------------------------|
| Copper    | 380                         | 8900            | 400                      |
| XLPE      | 0.3                         | 1400            | 2200                     |
| Soil      | 1.0                         | 2700            | 840                      |
| Duct      | 1.2                         | 2200            | 580                      |

The steady-state temperature simulation and transient temperature simulation were used to build the transient thermal model of this example. Steady-state temperature simulations under different currents were performed to get the thermal resistance after multiple average by analytical method. The step response of current-temperature was simulated by transient calculation. Thermal capacity were solved by genetic algorithm.

Because the model depend on the heat flow, the ac resistance and electro-thermal couple were not considered in the process of model construction. When we calculated the parameters in the model, the input was loss and the output was temperature. After we got the model, the electro-thermal couple could be realized by few step iteration.

Firstly, the steady-state simulation were performed by CYMCAP. The input loss and simulation result were shown in Table 2. $\theta_c$ and $\theta_s$ were the cable core temperature and sheath temperature respectively.

### Table 2. The simulation results

| Condition | Qc (W) | $\theta_c$ (°C) | Qs (W) | $\theta_s$ (°C) |
|-----------|--------|-----------------|--------|-----------------|
| 1         | 1.99   | 29.1            | 0.15   | 26.6            |
| 2         | 3.53   | 36.1            | 0.27   | 31.6            |
| 3         | 7.95   | 55.6            | 0.6    | 45.5            |
| 4         | 10.82  | 68.0            | 0.82   | 54.3            |
| 5         | 14.13  | 82.1            | 1.07   | 64.2            |
| 6         | 17.88  | 97.9            | 1.35   | 75.2            |

The dielectric loss in 10kV power cables was very small and it could be neglected in the transient thermal model. For the steady-state simulation, the thermal capacity and inductor all could be neglected. The thermal resistance could be calculated easily. $R1=(\theta_c-\theta_s)/Qc$, $R3=\theta_s/(Qc+Qs)$. The thermal resistance $R1$ and $R3$ were 1.267 K·m/W and 2.974K·m/W, respectively. The resistance of cable core and sheath could be calculated by $Q/I^2$. The cable core resistance and sheath resistance were $6.134e-5 \Omega/m$ and $4.645e-6\Omega/m$. 
Secondly, the transient simulation was performed to determine the thermal capacity and thermal inductor. The input current was a step current. The current at 0- was 0A and the current at 0+ was 360A. The transient simulation time was 96 hours. The calculation step length was 0.1 hours. The other parameters were calculated by genetic algorithm. The range value of C1, C2 and R2 were set by experience. C1, C2 ∈ (0,100), C3 ∈ (0,2000), R2 ∈ (0.001,10). The code was binary code. The number of initial population was 200. The crossover probability was 0.75. The mutation probability was 0.3. The max generation was 100. The fitness function was

\[
\text{fitness} = \sum_{i=1}^{960} \left[ (m_c(i) - \text{means}_c(i))^2 + (m_s(i) - \text{means}_s(i))^2 \right]
\]  

(1)

\(m_c(i)\) and \(m_s(i)\) were the core temperature and sheath temperature calculated by transient thermal circuit. \(\text{meas}_c(i)\) and \(\text{meas}_s(i)\) were the core temperature and sheath temperature calculated by CYMCAP.

The stopping criteria was the fitness function value less than \(960 \times 0.3 \times 0.3 \times 2 = 172.8\). It meant that the temperature error at each point was less than 0.3℃. The genetic process was performed by MATLAB. At last, the fitness value was 13.87<172.8 and the transient thermal model parameters were obtained.

\[
C_1 = 22.02 \text{ (W·s} / (\text{K·m})) \quad C_2 = 35.17 \text{ (W·s} / (\text{K·m})) \\
R_2 = 1.53 \text{ (K·m} / \text{W}) \quad C_3 = 80.47 \text{ (W·s} / (\text{K·m}))
\]

The genetic process was shown in Figure 4. The comparison between the analytical result of transient thermal model and the result of CYMCAP was shown in Figure 5. It proved the effectiveness of the transient thermal model as shown in Figure 1.

![Figure 4. Parameter extraction program based on genetic evolution algorithm.](image)

![Figure 5. Comparison of calculation results.](image)

3.2. Application and Verification

The environment temperature was 20℃. The current curve applied in cable 1 was shown in Figure 6. When \(I_r\) was the rating current. \(I_r\) was applied in cable 1 at 0-24h. \(0.5 \times I_r\) was applied in cable 1 at 24-48h. \(1.25 \times I_r\) was applied in cable 1 at 48-72h. \(0.75 \times I_r\) was applied in cable 1 at 72-96h. The results from transient thermal model and CYMCAP were shown in Figure 6 and Figure 7. The maximum error between transient thermal model and CYMCAP was 1.24. It was less than 2K. It proved that the transient thermal mode could fit the operation demand.

![Figure 6. The comparison of cable core temperature rise results.](image)

![Figure 7. The comparison of cable sheath temperature rise results.](image)
4. Conclusion
The power cables in duct are used widely in city transmission power lines. A transient thermal model of single power cable in duct to realize fast calculation of cable core temperature was studied in this paper.

The transient thermal model with a balance thermal resistance and balance thermal inductor was designed. The steady state parameter was obtained by steady state temperature simulation. The transient parameters were calculated by transient temperature simulation and genetic algorithm. The results by transient thermal model were compared with CYMAP. The comparison proved that the transient thermal model could simulate the transient temperature rise of cable core and sheath accurately.

After the transient thermal model was acquired, the model could be used to obtain the core temperature and sheath temperature easily and fast by simple thermal calculation and real-time modification of loss. The online cable temperature analysis of running power cable could be performed by the model.

The data to extract the model parameters not only come from general software, but also from numerical simulation or measurement. The data source is abundance. The effect of complex environment on accuracy of numerical simulation can be avoid. The diversity of data source improve the environment adaptive of the model. It is important to deepen the application of the model in real power cable lines.

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