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Rapid Transfer Matrix-Based Calculation of Steady-State Temperature Rises in Cable Ducts Containing Groups of Three Phase Cable

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ABSTRACT This paper presents a heat transfer matrix and superposed thermal field-based method that can rapidly calculate steady state temperature rises in three-core cable groups laid in ducts. The temperature rise of any cable is a combination of self-reaction and interaction from other cables. A heat transfer matrix is formed by self-reaction coefficient and interaction transfer coefficient representing the thermal characteristics of the cable groups in ducts. The heat transfer matrix can be obtained by enough samples including temperature rise and cable losses based on numerical analysis, trial or commercial software. Rapid calculations can then be performed by simplify iteration of temperature-loss. Extraction of the transfer matrix using CYMCAP ampacity and temperature calculation software and application of the fast calculation method are illustrated and compared, confirming the feasibility and relative simplicity and accuracy of the fast calculation method.

INDEX TERMS Power cables, heat transfer matrix, ducts, temperature rise, fast calculation method.

I. INTRODUCTION

Large numbers of power cables make up the urban power grid in cities such as Beijing, Shanghai, Guangzhou and Shenzhen. In urban areas, cables carrying 110kV or under are usually either directly buried or laid in pipes or ducts [1]. In view of the close proximity of the cables grouped in ducts and the likely heat transfer between them, a relatively conservative ampacity is usually adopted in the design stage, with fixed values being given to the different voltages and their cross-sections without considering the actual nature of other cables in the ducts. As the ongoing accelerating of urban construction pushes up social electricity consumption. Load hot-spots have started to form in some areas. In these areas, the ampacity of some cables has approached or reached its designed ampacity value. As a result, some cable are often overload in certain peak periods, such as in summer and winter. Load shifting or limiting is usually operated by suppliers which brings inconvenience for users. Suppliers also often seek to replace old cables with large capacity cables to meet the load demand. However, the new construction and modification of cables is often affected by municipal administration policies, the scope for excavation, different modes of operation, drainage resources and numerous other factors. Implementing such projects is very difficult. Furthermore, all the selection is based on the designed ampacity value. The present situation is that the quality of equipment is frequently inadequate and asset efficiency is low. As a result, power suppliers need a simple, practical and accurate way to evaluate temperature rise of cable groups in ducts rapidly so that they can dispatch maintenance and repair crews in a timely fashion.

There are both analytic and numerical methods for calculating the steady state temperature rise in groups of cables [2]–[13]. Analytical approaches are mainly based on the IEC-60287 standard (the corresponding domestic standard in China is JB/T10181) and the Neher-McGrath model,

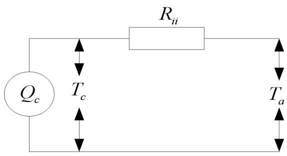

FIGURE 1. **Simplified thermal circuit.**

which are only applicable to simple cable systems and can only identify basic boundary conditions [14], [15]. Numerical methods include boundary element, finite difference and finite element approaches. These can simulate actual boundary conditions and be applied to more complex cable systems. However, numerical approaches depend on significant levels of professional knowledge and sophisticated tools because of the huge amount of calculation. They are therefore not well-suited to real-time operational load regulation because of their large calculations and low implementation efficiency [16]–[19].

Examination of the current state of the art regarding the calculation of steady state temperature rises and associated cable analysis reveals that there is no effective method for rapidly assessing temperature rises in complex groups of cables laid in ducts. By drawing upon thermal field superposition principles, this paper investigates the thermal characteristics of groups of cables laid in ducts. A transfer matrix is established. Combined with simple iteration of temperature-loss calculations, the transfer matrix achieves the rapid calculation of steady-state temperature rises for multiple-loop cables under multiple operating conditions, multiple boundary conditions.

II. COMPUTATIONAL PRINCIPLES AND PROCESS

A. THE BASIC PRINCIPLE

When undertaking actual calculations, a three-phase current is basically the same operationally as a single-phase one. So a three-phase cable can be treated as a single-phase cable by setting aside the temperature difference for thermal analysis. Actually, the thermal conductivity of the core conductor, metal sheath and armor-layer is much larger than that of the duct and the surrounding soil when taking into account the differences in their geometric dimensions and physical properties. The thermal resistance of cable is easy to be obtained by a simple formula. Because of the large size and variable thermal conductivity of soil, it is difficult to obtain the actual thermal resistance of the soil. Because of the uniqueness of the thermal field, a simplified thermal model shown in Figure 1 describes the complex heat transfer process in underground cables in ducts.

R_{ii} represents the total thermal resistance between the core and ambient environment. Q_c is the total loss for the conductor. T_c is the temperature rise in the cable core. T_a is the ambient temperature. The heat transfer can be described as follow:

$$T_c - T_a = R_{ii} \cdot Q_c \tag{1}$$

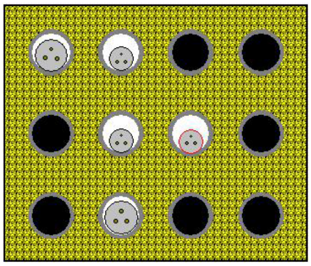

FIGURE 2. **Five three-core cables in 3*4 ducts.**

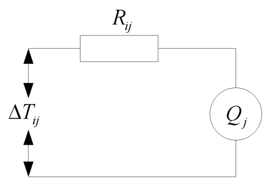

FIGURE 3. **Simplified thermal circuit.**

For underground power cables, the line length of a group of power cables is nearly infinite in relation to their cross-section and the thermal diffusion cross-section. So, models of the thermal field of power cables laid in ducts can be simplified to two-dimensional thermal field models for the purposes of analysis and calculation [20]. Ducts with five three-core power cables is shown in Figure 2.

For groups of cables laid in ducts, there are different heat transfer medium, such as cable, soil, ducts and air in the pipes. The heat transfer mode in cable, soil and ducts is heat conduction. The heat transfer is complex for air in pipes. There are three heat transfer mode, heat conduction, heat convection and heat radiation, between external surface of cable and internal surface of ducts. Working upon the principle of the superposition of thermal fields [21], the analysis of complex heat transfer process can be neglected and the interaction of a multiple-loop cable can be discretized into a combination of single-loop cables. The temperature rise in any cable is not only caused by the self-cable, but also by nearby cables. The self-action of any cables can be described using a self transfer coefficient as shown in Figure 1. The interaction between any two cables can be described using a mutual heat transfer coefficient as shown in Figure 3.

R_{ij} represents the total thermal resistance between the cabel i and cable j. Q_j is the total loss for the conductor in cable j. ΔT_{ij} is the cable core temperature rise in cable i caused by cable j. The heat transfer between two cables can be described as follow:

$$\Delta T_{ij} = R_{ij} \cdot Q_j \tag{2}$$

Then a transfer matrix can be constructed. The rapid calculation of steady-state temperature rises across multiple operating conditions and for multiple-loop cables can thus be achieved by simply iterating the 'temperature-loss' across the component elements.

B. ESTABLISHING THE TRANSFER MATRIX

It can be assumed that the heat dissipation temperature at each boundary of thermal field is constant. The numbers of the cables are, respectively, 1-i. $a_{i,i}$ is the thermal conductivity of cable i and $a_{i,j}$ is the mutual thermal conductivity of cable i and cable j. According to the duality principle, $ai_{,j} = a_{j,i}$. The same goes for the others. The transfer matrix is shown below.

$$A = \begin{bmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,i-1} & a_{1,i} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,i-1} & a_{2,i} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{i-1,1} & a_{i-1,2} & \cdots & a_{i-1,i-1} & a_{i-1,i} \\ a_{i,1} & a_{i,2} & \cdots & a_{i,i-1} & a_{\mathrm{i,i}} \end{bmatrix}$$

The temperature rise matrix for the cable core and the total loss matrix for the cable can be defined, respectively, as follows.

$$T_c = \begin{bmatrix} T_{c1} & T_{c2} & \cdots T_{ci} \end{bmatrix}^T$$
$$Q_c = [\, q_{c1} \quad q_{c2} \quad \ldots q_{\mathrm{ci}} \,]^T$$

The overall matrix equation is then:

$$A \cdot T_c = Q_c \tag{3}$$

The temperature rise data T_c and cable loss Q_c according to different operating conditions can be obtained through prior numerical calculation, commercial software, or experiment. Then, the transfer matrix A representing the steady-state thermal characteristics of the cross-section of the cable in ducts can be obtained by Q_c/T_c.

As the thermal characteristic parameters for each component in the cable, duct and surrounding medium, remain more or less unchanged within the range of operating temperatures, the transfer matrix does not change according to the calorific value or temperature of the cable core. So, when we know the current load in cable and obtain the losses in cables, the temperature rise of cables will be known and we can manage the cable load according to the temperature limit of cables.

Eq (3) is basically consistent with the nodal voltage method used in circuit analysis, which provides a theoretical basis for the discussion of thermal fields by thermal-electrical analogy. At the same time, there are non-unitary heat dissipation boundary conditions that are decided by practical circumstances. So, the boundary conditions for calculating the thermal field, such as the ambient temperature, are not a constant. According to the electrical circuit analysis method, the nodal voltage is decided by the reference point and source. Therefore, Eq (3) can realize the calculation of temperature rise under different ambient temperature and the real temperature of cable core is the sum of temperature rise and ambient temperature [22].

C. COMPUTATIONAL FLOW

When the transfer matrix has been obtained, the temperature rise for each cable according to a specific set of combined current conditions can be calculated using the following steps:

TABLE 1. Parameters of calculation.

Cable	Position x(m)	Position y(m)	Voltage (kv)	Cross-Section Area(mm^2)	Designed Current(A)
1	-0.69	-0.87	10	400	360
2	-0.46	-0.86	10	240	285
3	-0.46	-1.10	10	240	285
4	-0.20	-1.10	10	240	285
5	-0.46	-1.34	35	400	360

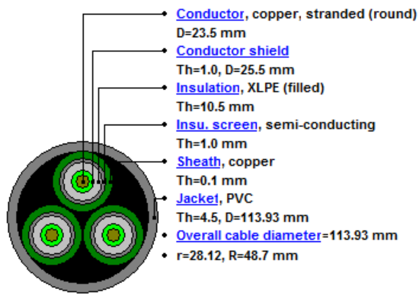

FIGURE 4. Cross-sectional data of the cable 5.

Step 1: the initial loss for the cables at ambient temperature can be obtained by using electrical knowledge(the specific calculations can found in [4]).

Step 2: The initial temperature rise for the outer sheath can be obtained from Eq (3) then the initial core temperature rise can be obtained from Eq (1).

Step 3: By iterating the 'temperature-loss', the losses for the core conductor, the eddy-current losses in the metal sheath and the armor layer, and the dielectric losses in insulation, can be obtained according to the initial core temperature rise and initial outer-sheath temperature rise. New losses are formed too.

Step 4: Step 2 and 3 are repeated until the maximum variation in temperature rise for each cables core and outer sheath obtained by two iteration is less than 0.1K, which can be considered as a steady-state temperature rise for this set of conditions.

The detailed calculation process is shown in the following example.

III. APPLICATIONS

A. DESCRIPTION

The object of calculation is a group of cables laid in duct with five three core power cables. The duct has a 4*3 hole structure as shown in Figure 1. The height of the duct is 1.1m, the width is 1.5m and the distance between the top of the duct and the ground surface is 0.7m. The distance between nearby two holes is 0.23m. The thermal resistance coefficient of the duct is 1.2K·m/W, the thermal resistance coefficient of the soil is 1.0K·m/W, and the ambient temperature is 20°C. Within the pipe, there is a group of four 10kV(cable 1,2,3 and 4) three-core power cables and one 35kV(cable 5) three-core power cables. The cable parameters are shown in Table 1. A typical cable cross section and its structural parameters are shown in Figure 4.

B. TRANSFER MATRIX SOLUTION

For convenience, CYMCAP (a soft ware designed by CYME) was used to calculate the sample data. Sample currents were generated randomly as shown in Table 1.

When the currents were input in CYMCAP model, the losses Q_c, the cable core temperature rises T_c and the cable sheath temperature rise T_s were calculated using CYMCAP software.

$$Q_c = \begin{bmatrix} 8.94 & 16.83 & 21.99 & 20.46 & 7.11 \\ 15.57 & 2.76 & 3.54 & 9.09 & 3.12 \\ 1.26 & 5.97 & 24.72 & 11.94 & 18.12 \\ 2.37 & 17.49 & 3.63 & 5.04 & 11.34 \\ 15.18 & 4.8 & 16.14 & 2.4 & 7.62 \\ 14.73 & 3.69 & 2.55 & 22.95 & 1.53 \\ 3.54 & 5.97 & 8.94 & 28.29 & 1.89 \\ 12.15 & 8.22 & 27.15 & 6.75 & 15.69 \\ 1.17 & 10.77 & 10.95 & 6.63 & 15.06 \\ 7.71 & 16.47 & 7.74 & 5.04 & 15.9 \end{bmatrix}$$

$$T_c = \begin{bmatrix} 26.1 & 63.9 & 79.6 & 74 & 27.3 \\ 21.7 & 16.6 & 19.2 & 32.1 & 11.3 \\ 15.6 & 32 & 83.1 & 49.7 & 34.4 \\ 12.1 & 55.2 & 22.1 & 24.1 & 20.3 \\ 24.7 & 25.5 & 55.2 & 18.7 & 19.3 \\ 23.1 & 21.9 & 20.6 & 71 & 13.2 \\ 13.9 & 28.5 & 38.6 & 86.7 & 15.6 \\ 27.5 & 40.5 & 90.9 & 37.6 & 33.7 \\ 11.7 & 39.3 & 42.5 & 30.2 & 25.8 \\ 19.8 & 56.2 & 36.6 & 27.6 & 27.7 \end{bmatrix}$$

$$T_s = \begin{bmatrix} 25.3 & 62.3 & 77.5 & 72.1 & 26.4 \\ 20.5 & 16.4 & 18.9 & 31.3 & 11 \\ 15.5 & 31.5 & 80.7 & 48.5 & 32.1 \\ 11.9 & 53.6 & 21.8 & 23.7 & 18.9 \\ 23.5 & 25 & 53.7 & 18.5 & 18.3 \\ 21.9 & 21.6 & 20.3 & 68.8 & 13 \\ 13.6 & 28 & 37.8 & 84 & 15.4 \\ 26.6 & 39.8 & 88.3 & 37 & 31.7 \\ 11.6 & 38.3 & 41.5 & 29.6 & 23.9 \\ 19.2 & 54.6 & 35.9 & 27.1 & 25.7 \end{bmatrix}$$

It should be pointed out that 1) the transfer matrix can be obtained in various ways, such as numerical analysis, experiment, or IEC-60287 formula. The base data for establishing and validating the transfer matrix used here was provided with the general CYMCAP software for calculating the temperature rise in cables. 2) the number of calculation samples should be not less than the cable number. For practical application, 10 sample data were used to obtain the heat transfer matrix so as to ensure their orthogonalization and reduce errors.

The heat transfer matrix to describe the interaction between cable loss and cable core temperature rise obtained using

TABLE 2. Current in Cables.

Cable 1 Current(A)	Cable 2 Current(A)	Cable 2 Current(A)	Cable 2 Current(A)	Cable 2 Current(A)
245	262	301	290	212
324	90	107	188	133
89	148	320	218	347
124	267	109	134	272
320	130	256	81	220
315	110	85	308	82
153	148	186	343	96
286	178	336	159	322
86	206	208	157	315
227	259	172	134	324

Eq (3) is

$$A_c = \begin{bmatrix} 0.9528 & -0.0797 & -0.0566 & -0.0378 & -0.1286 \\ -0.0809 & 0.3698 & -0.0249 & -0.0204 & -0.0444 \\ -0.0594 & -0.0243 & 0.3735 & -0.0285 & -0.0931 \\ -0.0399 & -0.0186 & -0.0259 & 0.3647 & -0.0814 \\ -0.1275 & -0.0464 & -0.0888 & -0.0730 & 0.9465 \end{bmatrix}$$

The heat transfer matrix to describe the interaction between cable loss and cable sheath temperature rise can be obtained using the same way.

$$A_s = \begin{bmatrix} 1.0331 & -0.0861 & -0.0606 & -0.0396 & -0.1618 \\ -0.0890 & 0.3848 & -0.0256 & -0.0215 & -0.0522 \\ -0.0643 & -0.0256 & 0.3890 & -0.0292 & -0.1080 \\ -0.0436 & -0.0199 & -0.0268 & 0.3792 & -0.0926 \\ -0.1558 & -0.0534 & -0.1024 & -0.0856 & 1.0780 \end{bmatrix}$$

The diagonal elements in the heat transfer matrix are basically equal, which proves the accuracy of the calculation. In order to meet the need of subsequent calculations, a new transfer matrix is generated after averaging the diagonal elements. The heat transfer matrix to calculate the sheath temperature rise can be performed as same way.

$$A_{c1} = \begin{bmatrix} 0.9528 & -0.0803 & -0.0580 & -0.0388 & -0.1280 \\ -0.0803 & 0.3698 & -0.0246 & -0.0195 & -0.0454 \\ -0.0580 & -0.0246 & 0.3735 & -0.0272 & -0.0910 \\ -0.0388 & -0.0195 & -0.0272 & 0.3647 & -0.0772 \\ -0.1280 & -0.0454 & -0.0910 & -0.0772 & 0.9465 \end{bmatrix}$$

$$A_{s1} = \begin{bmatrix} 1.0331 & -0.0875 & -0.0625 & -0.0416 & -0.1588 \\ -0.0875 & 0.3848 & -0.0256 & -0.0207 & -0.0528 \\ -0.0625 & -0.0256 & 0.3890 & -0.0280 & -0.1052 \\ -0.0416 & -0.0207 & -0.0280 & 0.3792 & -0.0891 \\ -0.1588 & -0.0528 & -0.1052 & -0.0891 & 1.0780 \end{bmatrix}$$

In addition, by using the data in Table 2, the parameters for the core AC resistance, sheath AC resistance, dielectric loss and total thermal resistance of the core-sheath as shown in Table 3 can be obtained, assuming the cable has an ambient temperature of 20°C. The core resistance has a positive temperature coefficient. The sheath resistance has a negative temperature coefficient. The influence of dielectric loss on temperature was analyzed by a specific calculation method

TABLE 3. AC resistance, dielectric loss and thermal resistance of each cable.

Cable	Core resistance (Ω/m)	Sheath resistance (Ω/m)	Dielectric loss (W/m)	"core-sheath" thermal resistance (K/W*m)
1	4.784E-05	1.278E-06	0.03	0.250
2	7.655E-05	1.033E-06	0.18	0.282
3	7.655E-05	1.033E-06	0.18	0.282
4	7.655E-05	1.033E-06	0.18	0.282
5	4.702E-05	1.732E-06	0.29	0.377

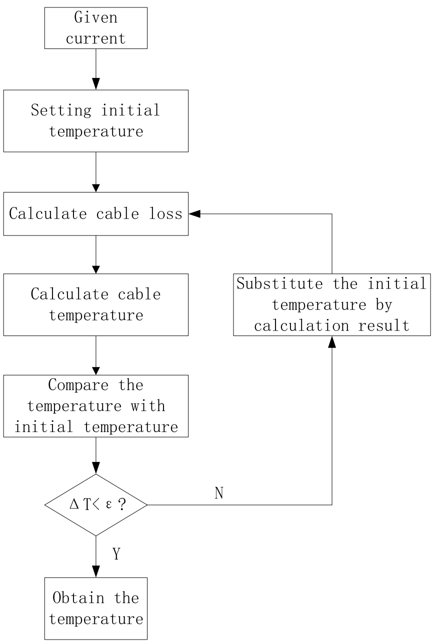

FIGURE 5. Thermal electrical coupling procedure.

TABLE 4. Iterative process data.

P_0	T_{s0}	T_{c0}	Error-t_s	Error-t_c	Change-max
23.63	32.91	34.83	4.09	4.37	/
10.17	40.99	41.92	6.71	6.98	/
3.53	26.06	26.39	3.54	3.61	/
11.22	42.47	43.50	7.13	7.40	/
9.66	21.96	23.14	0.74	2.56	/
		↓↓↓			
P_1	T_{s1}	T_{c1}	Error-t_s	Error-t_c	Change-max
26.61	37.02	39.19	-0.02	0.01	4.36
11.62	46.52	47.59	1.18	1.31	5.67
3.80	28.81	29.17	0.79	0.83	2.78
12.90	48.38	49.57	1.22	1.33	6.07
10.42	24.31	25.58	-1.61	0.12	2.44
		↓↓↓			
P_2	T_{s2}	T_{c2}	Error-t_s	Error-t_c	Change-max
26.99	37.54	39.74	-0.54	-0.54	0.55
11.82	47.26	48.34	0.44	0.56	0.75
3.82	29.15	29.51	0.45	0.49	0.34
13.13	49.19	50.40	0.41	0.50	0.83
10.49	24.59	25.88	-1.89	-0.18	0.30
		↓↓↓			
P_3	T_{s3}	T_{c3}	Error-t_s	Error-t_c	Change-max
27.04	37.60	39.81	-0.60	-0.61	0.07
11.85	47.36	48.44	0.34	0.46	0.10
3.83	29.19	29.56	0.41	0.44	0.04
13.16	49.30	50.51	0.30	0.39	0.11
10.50	24.63	25.91	-1.93	-0.21	0.04
		↓↓↓			
P_4	T_{s4}	T_{c4}	Error-t_s	Error-t_c	Change-max
27.04	37.61	39.82	-0.61	-0.62	0.01
11.85	47.37	48.46	0.33	0.44	0.01
3.83	29.20	29.56	0.40	0.44	0.01
13.17	49.31	50.52	0.29	0.38	0.01
10.51	24.63	25.92	-1.93	-0.22	0.00

proposed in paper [4] and that proved the dielectric loss can be neglected.

C. APPLYING THE TRANSFER MATRIX

For the purpose of the example, it is assumed that load forecasting and operational mode arrangements require that the cable currents within the duct will be 400A for cable 1, 202A for cable 2, 107A for cable 3, 211A for cable 4 and 250A for cable 5. The current for cable 1 exceeds its designed current of 360A. This makes it necessary to assess the temperature rise of this cable group.

Based upon operational experience, the ambient temperature will be taken to be 28°C. The calculation results provided by CYMCAP are as follows: the sheath and core temperature rise for cable 1 are 37K and 39.2K, repectively; the sheath and core temperature rise for cable 2 are 47.7k and 48.9K; for cable 3, the figures are 29.6K and 30.0K; for cable 4, 49.6K and 50.9K; and for cable 5, 22.7K and 25.7K.

To use the transfer matrix method to solve the above problem, electro-thermal coupling must be performed as follow:

The iterative calculation process for the example is shown in Table 4. After only five steps, the maximum change is 0.01 and the calculation converges. If compared with direct calculation results, the maximum deviations for the steady-state temperature rise for the core and the sheath are 0.44K and 0.40K, respectively, which can meet actual operational needs.

On the basis of this calculation, although cable 1 exceed its designed current, the operating temperature of the cable group will remain within the allowable operating temperature for the equipment, so it can operate normally without any need to transfer or limit the load, or upgrade the equipment.

IV. CONCLUSION

This paper has focused on the development of a transfer matrix and a rapid algorithm to calculated the steady-state temperature rise of three-phase cable groups laid in ducts. The main conclusion are as follows:

Based on the principle of thermal field superposition, the interaction of three-phase cable groups laid in ducts has been described using a transfer coefficient and a transfer matrix composed of bundled parameters that can reflect the steady-state thermal characteristics of the groups cross-section.

Given the current for each cable, the initial loss for each cable is obtained using prior electrical knowledge. The initial core temperature rise and sheath temperature rise for each cable is then obtained using the transfer matrix. A simple iteration of the combined 'temperature-losses' enables the corresponding temperature rise for each cable to be calculated accurately and quickly according to the specified current.

The extraction of the transfer matrix using the commercial software CYMCAP and the alternative application of the fast calculation method were compared using a duct cable example to illustrate the effectiveness of the approach. The viability, simplicity and accuracy of the combined transfer matrix and fast algorithm for calculating, steady-state temperature rises in three-phase cable groups in ducts has been proven to meet the operational requirements of power supply.

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