Research on the Fast Calculation Model for Transient Temperature Rise of Direct Buried Cable Groups

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***Abstract*- In this paper, a method based on time domain response and superposition principle of heat conduction field is studied in this paper. It can realize the quick calculation of transient temperature rise of direct buried cable. The combined action of cable groups is discrete as a combination of multiple cables alone. Self - heating of a single cable can be described by a self - response model. The mutual influence between the cable can be described by mutual response model. And then the integrated temperature rise of the cable core can be obtained through node temperature rise coupling method. So the fast calculation of the transient temperature rise is realized. In the example verification, the model parameters are extracted by using the common software CYMCAP. And then the transient temperature rise process of the typical working condition can be calculated. Finally, compared with the software results, the validity of the method is verified.**

***Index words*- Soil direct burial, cable group, transient temperature rise, lumped parameter, heat conduction.**

I. Background

Shanghai power grid has a large number of power cables. There are four main ways of laying：soil direct burial, pipes, grooves and tunnels. In electricity area of 110kV and below voltage grade, especially in urban areas, soil direct burial is the main means of laying. With the increase of commercial and resident power supply load, the peak of summer peak and the peak of winter peak have a short, overcurrent load current. This may affect the safe operation of the equipment.

The longer thermal time constants of the buried cable group need to be taken into consideration. Although the short time overcurrent may not lead to excessive temperature rise, due to the existing technical conditions, the underground cable cannot be assessed accurately, especially actual transient temperature of cable group under the different load current combination. The operating department generally tends to meet load demand by replacing large capacity cables. But the new construction and renovation of cables are often influenced by the municipal, excavation and operation methods. The project is beset with difficulties. And the equipment utilization is insufficient. The asset efficiency is low.

Because it is not generally possible to obtain the core temperature by direct measurement, especially the transient temperature of the core in real time. The technical personnel proposed the engineering formula method, numerical algorithm or indirect measurement method based on test results to master the core temperature. The engineering formula method is used to analyze the steady-state temperature rise[1-5]. The function of this method is very limited for transient temperature rise, especially for multi-back cable transient temperature rise; The numerical algorithm has developed rapidly in recent years due to its adaptability and the development of computing tools[6-11]. But for the actual running cable, the demand of getting the transient temperature rise of the cable core in time cannot be satisfied by numerical method because the laying section and the combination of the working condition are very complex, the requirements of personnel ability and resource allocation are high, and the calculation is huge. Indirect measurement method is used to obtain the surface temperature of the cable by adding optical fiber measuring temperature, and then the temperature of cable core is calculated[13-20]. However, there are some defects in practice: This method deeply relies on the health condition of the temperature measuring device. Defects such as temperature measurement deviation and transmission communication will directly restrict the selection of cable equipment operation. Considering that a cable usually has a number of sections that need to be monitored, this requires a multi-set temperature measuring device. In turn, the reliability of the overall system is low. In order to improve the overall reliability of the device and the system, it is possible to adopt the method of enhancing redundant design, even multiple sets and loading. For the cable group with multiple cables, this not only increases the investment of the device and the system significantly, but also brings a huge amount of work to the follow-up maintenance. This is the main reason why this method cannot be widely used. It can be seen from the current development of cable temperature rise calculation and the application of the measurement technology that there is no effective method to adjust the fast calculation of complex cable group, especially a fast algorithm for dynamic temperature rise which can satisfy the actual operation needs. Therefore, the quick calculation of the transient temperature rise of cable group is very practical and necessary[21-24].

Based on the time-domain response characteristic and the method of superposition principle of heat conduction field, this paper presents a lumped parameter model of the "dispersion + combination" cable group transient temperature rise. The heat and heat transfer process of the cable is described by the model of the self-response model and the mutual response model of cable heating. The combined temperature rise of the cable core is obtained through node temperature rise coupling and the real-time correction of the loss. Thus, the quick calculation of transient temperature rise is realized.

II. Cable group transient temperature rise model

2.1 Principle of transient model

The heating of cable groups depends on cable loss and the thermal characteristics of the section， the former has a definite correspondence with operating current and operating temperature, which is widely used in engineering：The latter mainly depends on the geometrical parameters of the section and the physical parameters of each part, and the physical parameters are generally considered to remain unchanged at the operating temperature range. And that is the basis of the model. According to the theory of heat transfer and the time-domain response characteristic based on temperature rise, this paper considers the use of "dispersion model" to solve the different cables themselves and their influence, and the "combination" in the result (rather than the uniform thermal path model) reflects the whole process of temperature rise.

The transient temperature calculation model of cable core is shown in fig.1 (take two single core cables as example). On the top left is a self-response model of the cable 1. And on the right is a "cable 2 - cable 1" mutual response model. On the left down is a " cable 1 - cable 2" mutual response model. On the left right is a cable 2 self-response model. According to the principle of duality, in addition to heat, the specific values of the two mutual response model parameters are the same.

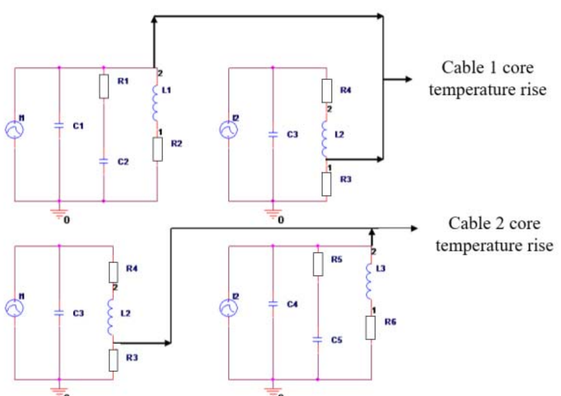


Fig.1 two single-core cable set total parameters transient thermal model

In the left self-response model, I1 is the loss (heat) of the cable. C1 is the equivalent heat capacity of cable 1 itself; C2 is the equivalent heat capacity of the soil section of cable 1. R1 is a thermo-resistance for the equivalent heat tolerance of the cable 1 soil section; R2 is the equivalent thermal resistance of cable 1 core to the environment; L1 is the equilibrium heat of equivalent thermal resistance of cable 1. The lower right model parameter is the same.

In the upper right mutual response model, I2 is the loss of cable (heat); R3 is the comprehensive thermal resistance of the core between cable 2-cable 1. R4, L2 and C3 have no explicit physical significance, which is used to generate different transition processes. The lower left model has the same meaning.

2.2 Transient model establishment and application procedure

The transient model's establishment and the application steps are shown in figure 2, where the single-line arrows are scattered and solved in order to establish the self-response model and the mutual response model. The two-line arrow is a composite application in order to get the core temperature.

The main steps include:

1) By numerical calculation and test, the N cable applying heat load separately, and calculate the response process.

2) According to the single thermal model and the temperature rise process of the N root cable, the aggregate parameter model of the self-response of each cable is established.

3) According to the interaction of N root cables, the model of the total parameters of the set of mutual response is established based on the "descending order" idea.

4) To get the heat load of cable, input the self-response model and the mutual response model respectively, and get the core temperature rise 1 and the core temperature rise 2, then add them to get the core temperature rise.

5) To correct the heat load from the core temperature in real time, we need to repeat the step4) to get the new core temperature.

6) Repeat step 5), so that the loop can obtain the transient temperature rise of the entire line core until the end of the calculation.

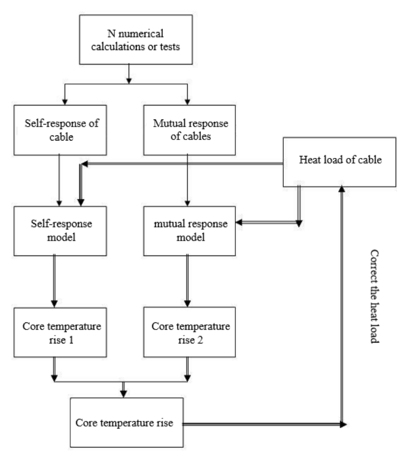


Fig. 2 extraction and application of model parameters

The temperature reference point of the model is the ambient temperature, and the calculation is not dependent on the epidermal temperature measurement. Since the model is not dependent on the heat or current size of the cable itself, it is only related to the thermal characteristics of the cable body, the laying conditions and the surrounding materials. Therefore, when the model is set up, changing the current of the cable doesn't have to be repeated with the numerical calculation, but it can be satisfied with the simple thermal calculation and the loss correction.

III. Model building and verification

3.1 Establishment of the model

The process of establishing a model is essentially using the aggregate parameters to simulate or extract the rules of the heat transfer process. The parameter extraction process of the model shown in figure 1 requires reference value calculation or test results. In this paper, the establishment of the model and the data base of the model verification is selected by the universal computing software CYMCAP.

(1) Calculation model

Cable group of calculation model as shown in figure 3, including 4 single core cables and a three core cable with time, the structural parameters of the cable as shown in figure 4, the installation parameters as shown in Table 1, the environment temperature is 20 ℃. The rated current of single-core cable is 1000A, and the rated current of three core cables is 1500A.

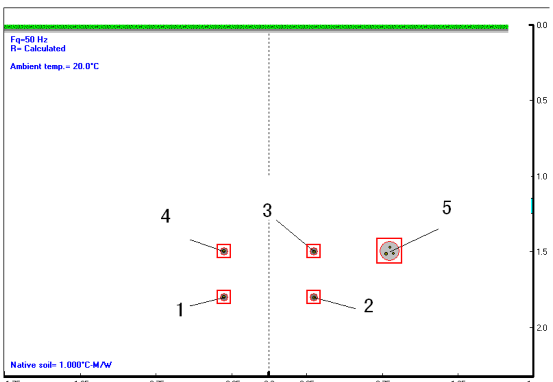
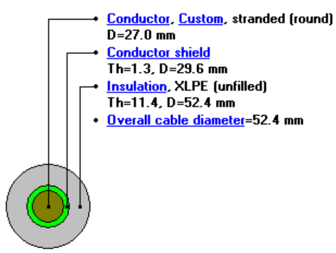
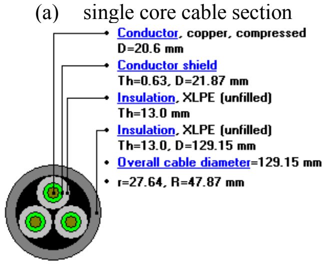


Fig. 3 Calculation model



(a) single core cable section



(b) three core cable sections

Fig. 4 schematic diagram of cable section

It needs to be pointed out that because the model focuses on the thermal characteristics of the section, for the sake of convenience, the temperature coefficient of setting the wire core resistivity is 1e-12 in the process of establishing the model, so as to ensure that the heat flow is constant, that is, the temperature influence of the cable ac resistance is not considered. In actual application, the heat flow (loss) of this moment can be obtained according to the cable temperature and the current value of the initial t moment. Input the heat(loss) into the model, we can calculate t + Δ t moment cable temperature rise. At this point, the core temperature is adjusted to get a new thermal flow, then input it to the model, and we can get the moment temperature rise value at t + 2 * Δ t moment. So until the end of computing cycle, we can obtain the transient temperature rise of the whole line core.

TABLE I
CABLE LAYING POSITION

Cable	center location(m)
1	(-0.3,1.85)
2	(0，1.85)
3	(-0.3，2.1)
4	(0，2.1)
5	(0.3，2.0)

(2) Calculation conditions and results

The steady state condition is to apply the rated current to the power cables, and the rest of cable current is 0, then the steady temperature rise of each cable can be obtained, as shown in Table 2.

In the transient condition, the rated current is applied to the cables in turn, the waveform is the step wave. The other cable current is 0. Then the transient temperature rise process of each cable is obtained. The calculation time is 64h.And the step is 0.1 h. Figure 5 shows the transient temperature rise of each cable core when the rated current is applied to cable 2. It is worth noting that from the perspective of heat transfer, the heating problem of the three-core cable is basically the same as that of single core cable. So in CYMCAP, only the average temperature of the three phases is given, and in this paper, three core cables are treated as single core.

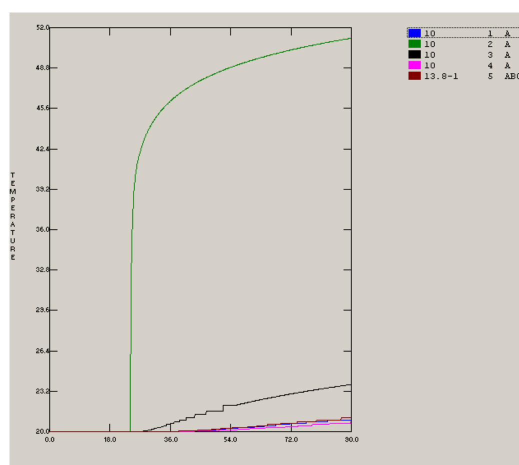


Fig. 5 the transient temperature rise of cable core under the condition of cable 2

(3) Extraction of total model parameters

The solution of each parameter in the model shown in figure 1 is implemented by analytic method and genetic algorithm. Taking the cable 2 self - response model and the " cable 2 - cable 1 " mutual response model as an example.

a) the equivalent thermal resistance of the cable 2 core to the environment.

TABLE II
CALCULATION RESULTS OF THE STEADY TEMPERATURE RISE OF EACH WORKING CABLE

Current carrying cable	Loss (W)	Cable 1 temperature rise (K)	Cable 2 temperature rise (K)	Cable 3 temperature rise (K)	Cable 4 temperature rise (K)	Cable 5 temperature rise (K)
1	36.95	32.5	9.6	8.5	13.5	6.5
2	36.95	9.6	32.5	13.5	8.5	10.3
3	36.95	8.5	13.5	32.5	9.6	10.6
4	36.95	13.5	8.5	9.6	32.5	6.3
5	55.35	9.7	15.4	15.8	9.4	57.2

TABLE III
CALCULATION CONDITION

Cable	0-24h	24-48h	48-72h	72-96h
1	500A	1000A	1000A	0A
2	500A	1000A	500A	1000A
3	500A	500A	500A	500A0
4	500A	1000A	0A	1000A
5	500A	1000A	500A	1000A

According to the model shown in figure.1, the equilibrium heat of the equivalent heat capacity, the equivalent heat capacity of the section and the equivalent thermal resistance of the section have been balanced in the steady-state temperature rise. Therefore, R6=32.5/36.95= 0.879.

b) the power of the cable is the equivalent of the equivalent heat capacity C4, the equivalent heat of the cross section C5, the equivalent heat of the cross section and the equilibrium heat of the resection of the R5, and the equivalent thermal resistance of the cross section L3.

The above parameters reflect the transition process of the cross section heat transfer, and the genetic algorithm can be adopted. The process is as follows. Among them, according to the thermal characteristics, R5*C5=L3/ R6.

Setting parameter range: according to the test experience, C4 (1, 50), C5 (10,500), R5 (0.01, 5), binary code. The initial population number is 100.The maximum genetic algebra is 500.The crossover probability is 0.75. And the variation probability is 0.2.

The fitness function is set: select the sum of the deviations of transient temperature rise response m (I) of the model shown in figure 1 and two curves of the transient temperature rise fem (I), as shown in figure 5, as the fitness function. Select:

$$fitness = \sum_{i=1}^{240}[m(i) - fem(i)]^2 \tag{1}$$

Setting convergence criterion: considering the anastomosis of thermal response, the average deviation of discrete points in the time period of (0-24) *0.1h is not greater than 0.2 k, and the fitness function value should be less than 240*0.2* 0.0.2 = 9.6. If the genetic algebra reaches the maximum genetic algebra and cannot satisfy the fitness function value less than 9.6, then the calculation fails.

Figure 6 shows the evolution of genetic algorithm. The results are: C1= 7.80, C2= 317.37, R2= 0.58, L1= 161.80.

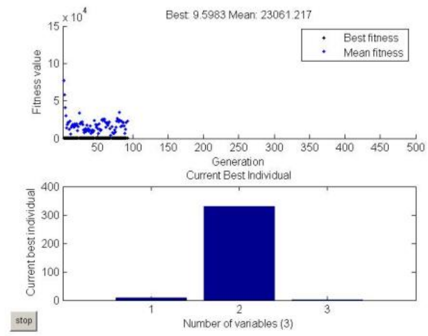


Fig.6 evolution of genetic algorithm is extracted from the response model parameters

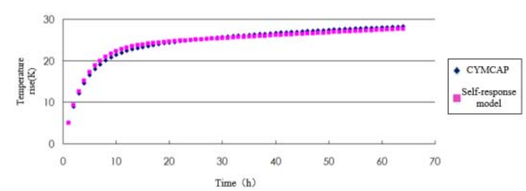


Fig 7 comparison of response calculation results of cable 2 transient temperature rise

2) "Cable 2-cable 1" mutual response model.

a) Equivalent thermal resistance of "cable 2- cable 1" line core to environment R3

According to the model shown in figure 1, the transition process of cable 1- cable 2 heat transfer has ended when steady temperature rise, so R3=9.6/36.95= 0.260.

b) Transition parameters C3, R4 and L2

The above parameters reflect the transition process of the cross section heat transfer, and the genetic algorithm can be adopted. The process is as follows.

Set parameter range: based on trial experience, C3 (100,2500)，R4 (0.01,10)，L2 (100,2500).Use binary code. The initial population number is 100.The maximum genetic algebra is 500. The crossover probability is 0.75. And the mutation probability is 0.2.

The fitness function is set: select the sum of the deviations of transient temperature rise response m (I) of the model shown in figure 1 and two curves of the transient temperature rise fem (I), as shown in figure 5, as the fitness function. Select:

$$fitness = \sum_{i=1}^{240}[m(i) - fem(i)]^2 \qquad (2)$$

Setting convergence criterion: considering the anastomosis of thermal response, the average deviation of discrete points in the time period of (0-24) *0.1h is not greater than 0.05 k, and the fitness function value should be less than 240*0.05*0.05= 0.6. If the genetic algebra reaches the maximum genetic algebra and cannot satisfy the fitness function value less than 0.6, then the calculation fails.

Figure 8 shows the evolution of genetic algorithms. The calculation results are: C3=987， R4=2.07，L1=1594.82.

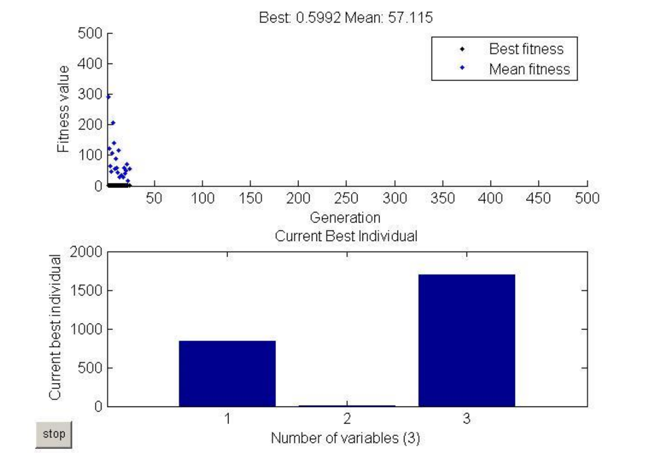


Fig. 8 the evolution process of genetic algorithm is extracted by the mutual response model parameters

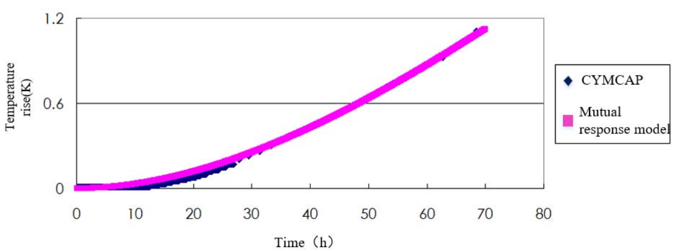


Fig. 9 comparison of calculation results of "cable 2-cable 1" transient temperature rise mutual response

(4) Parameter summary

Repeat the above procedure to get the overall model of the cable group, as shown in figure 3. the specific parameters, as shown in Table 1.

3.2 Validation of the model

In order to verify the validity of the model, the typical working conditions are selected and the common software CYMCAP is used for calculation. The results are shown in figure 10. And the calculated results are compared with the calculated results of the lumped parameters model, as shown in figure 11 ~ 15. The operating condition setting is shown in Table 3, which is the step load. The effect of temperature on loss is considered in this example.

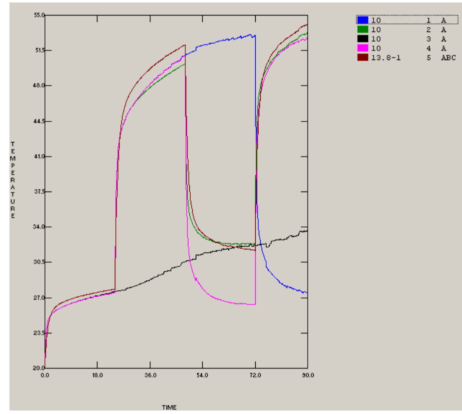


Fig. 10 results of CYMCAP calculation

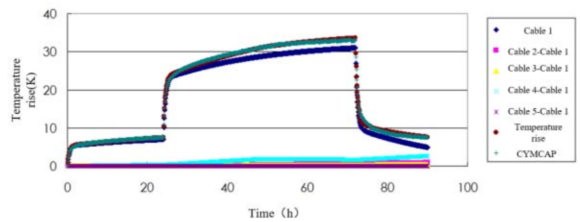


Fig. 11 comparison of calculation results of cable 1 transient temperature rise

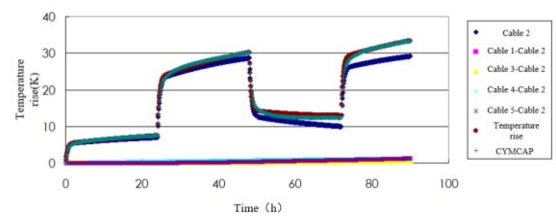


Fig. 12 comparison of calculation results of cable 2 transient temperature rise

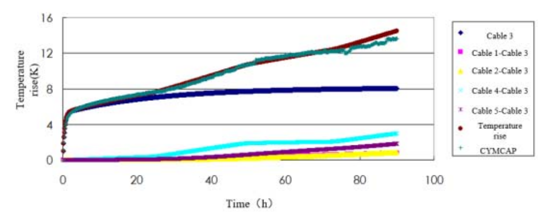


Fig. 13 comparison of calculation results of cable 3 transient temperature rise

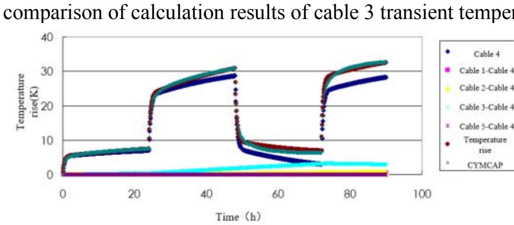


Fig. 14 comparison of calculation results of cable 4 transient temperature rise

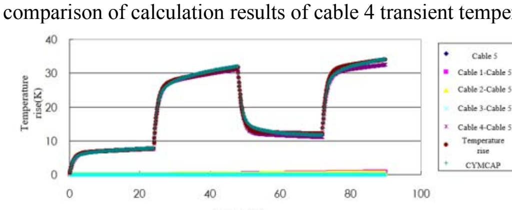


Fig. 15 comparison of calculation results of cable 5 transient temperature rise

The results show that the "dispersed + combination" lumped parameter model can simulate the transient temperature rise process of cable group well. In particular, it is possible to make a more accurate assessment of the effects between cables. This will provide direct basis for the adjustment and distribution of load in actual operation.

In practice, the time domain response of the environmental change to the cable core temperature rise can be obtained by using the numerical calculation software, referring to the method in this paper. The relative parameters can be obtained by genetic algorithm. The mutual response model of "environment-cable" is established. Thus, a complete "dispersion + combination" lumped parameter model of transient temperature rise of buried cable group is established.

IV. Conclusion

This paper mainly focuses on the study of the transient temperature rise and rapid calculation model of the direct buried cable group, which mainly obtains the following conclusions:

(1) Based on the principle of superposition of heat conduction field, the combined action of cable group is divided into a combination of multiple cables alone. Self - heating of a single cable can be described by a self - response model. The mutual influence between the cable can be described by mutual response model. And then the integrated temperature rise of the cable core can be obtained through node temperature rise coupling method. So the fast calculation of the transient temperature rise is realized.

(2) Based on the time domain response characteristics, a mutual response model of transient temperature rise between cables is proposed for the first time. Compared with the prevailing finite element method, the model has reliable accuracy and refined structure.

(3) The comparison between trial case and calculation of CYMCAP show that the transient temperature rise algorithm of the "dispersion + combination" buried cable group is reasonable and effective. This algorithm is simple and efficient. It can be used in real - time , convenient and fast calculation .Thus it meets the real-time needs of running.

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The appendix

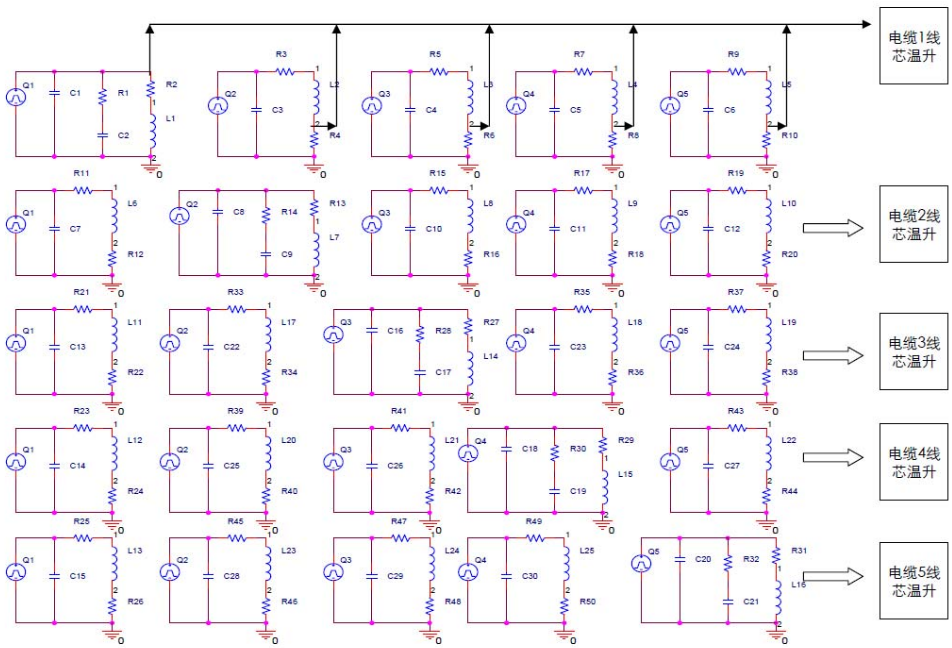

Fig. A1 The lumped parameter model of the "dispersion + combination" of cable group core transient temperature rise

TABLE I

THE LUMPED PARAMETER MODEL OF THE "DISPERSION+COMBINATION" OF CABLE GROUP CORE TRANSIENT TEMPERATURE RISE

Dispersion model			Parameter		
1-1	C0=7.80	C1=317.37	R1=0.580	R2=0.879	L1=161.80
1-2	C7=987	R11=2.071	L6=1594	R12=0.260	/
1-3	C13=1728	R21=0.099	L11=1375	R22=0.231	/
1-4	C14=713	R23=2.427	L12=38.698	R24=0.367	/
1-5	C15=4452	R25=1.026	L13=8295	R26=0.177	/
2-2	C8=7.80	C9=317.37	R14=0.580	R13=0.879	L7=161.80
2-3	C22=713	R33=2.427	L17=38.698	R34=0.367	/
2-4	C25=1728	R39=0.099	L20=1375	R22=0.231	/
2-5	C28=1340	R45=0.866	L23=1541	R46=0.278	/
3-3	C16=7.80	C17=317.37	R28=0.580	R27=0.879	L14=161.80
3-4	C26=987	R41=2.071	L21=1594	R42=0.260	/
3-5	C29=600	R47=2.756	L24=2004	R48=0.287	/
4-4	C18=7.80	C19=317.37	R30=0.580	R29=0.879	L15=161.80
4-5	C30=3658	R49=1.020	L25=8275	R50=0.179	/
5-5	C20=23.86	C21=626.728	R32=0.465	R31=0.677	L16=197.30

* : due to the symmetry of heat transfer between cables, the Table only lists some parameters, and the remaining parameters can be introduced by symmetry.