Lumped RC Thermal Network Method Applied to Transient Temperature Calculation of High Voltage Bushing and Its Insulation Life Assessment

Shiling Zhang
State Grid Chongqing Electric Power Company Chongqing Electric Power Research Institute, 401123, Chongqing, China
526793305@qq.com

Abstract. To analyze how the internal transient temperature of the high voltage condenser bushing varies with its short-time current carrying capacity and long-aging properties, lumped RC thermal network model applicable to the structure of HV bushing is proposed. This model considers three heat transfer modes of the conduction, the convection and the radiation, and the changing relationship between material properties and temperature and the thermal RC network topology is realized based on the MATLAB/SIMULINK. In the example of 550kV oil-SF₆ bushing, the calculation results of transient temperature thermal network are in good agreement with the actual temperature rise test results which proves effectiveness and practicality of lumped RC thermal network. We used the thermal network to confirm the periodic transient variation at the hottest spot of HV bushing and analyze the short-time current carrying capacity by step load curve fitting circadian cycle change load. Finite element method and thermal network method are used to get the electric and thermal stress respectively and HV bushing long-aging properties analysis was conducted based on classic ZHURKOV and CRINE electric and thermal combined aging model. This paper applies lumped RC thermal network method to transient temperature calculation and internal insulation life assessment of the HV bushing, reinforced classic bushing design method only considering rated steady-state operating conditions and has theoretical guidance on assessing short-time current-carrying capacity and long-aging properties in high voltage bushings.

1. Introduction
High-voltage capacitive bushing is common type of bushing in UHV/UHV power system at present. The traditional design of its thermal performance generally calculates the hottest steady-state temperature in the bushing core according to the rated current carrying capacity, so as to determine whether the rated operating temperature exceeds the heat-resistant performance requirements of the core insulation material. The rated operating temperature is the steady-state of the bushing under the continuous rated current carrying capacity[1-3]. However, load of the high-voltage power bushing in the actual transmission and distribution network can not always be rated. The temperature field of the bushing under variable load conditions belongs to the unstable heat flow field. Therefore, the method is needed to predict the transient change process of the temperature field of the bushing core under the actual continuous changing load. Ma et al. [4] calculates the temperature distribution of the fully enclosed external cooling induction motor for mini-car by finite element method. Mazzanti et al. [5] evaluates the thermal transient and overload capacity of high voltage bushing by thermal network method. Jasmin Smajic et al. [6] uses the equivalent thermal circuit model to analyze the heating and temperature rise of electromagnetic device in magnetic levitation system, and compares it with results of finite element simulation and temperature rise test. It can be seen that the calculation methods of the
Transient temperature field of high voltage power equipment mainly include finite element method, equivalent RC thermal network method, the actual temperature rise test, etc. Equivalent thermal network method has fast calculation speed and its accuracy depends on the number of network nodes, while the finite element method has high accuracy, but it has a large amount of calculation and is not convenient for repeated calculation.

In this paper, the specific mathematical expressions of lumped thermal resistance parameters representing three heat transfer modes, i.e. heat conduction, convection and radiation, are derived, and local RC heat network model suitable for the cross section of high-pressure casing is established. Transient temperature effect of high-pressure casing is analyzed by using this model. The comparison between the thermal network and the finite element calculation results proves that lumped RC heat network is applied to the casing structure. The local thermal network model is further extended to the complex structure of high pressure casing, and the topology of the complex thermal network is realized based on the MATLAB/SIMULINK, and the iterative calculation process considering change of casing material properties with temperature is given. The RC thermal network model is applied to the temperature rise analysis and the calculation of 550kV oil-SF6 bushing, and the results are in good agreement with the actual temperature rise test results. The effectiveness and practicability of lumped RC thermal network model for transient temperature calculation of high pressure casing are proved.

The aging factors of the HV insulation system include electrical, thermal and mechanical stresses. G. Mazzanti et al. used the electro-thermal aging model to evaluate the life of the cable insulation system and put forward corresponding theoretical system [7]. In this paper, the theoretical system of life assessment is further applied to the HV casing insulation system. The classical electro-thermal aging model considers that life loss of insulation system is due to cumulative effect of electro-thermal interaction, so the insulation life of high voltage bushing is determined by the periodic thermal transient process [8,9]. The stepped load curve is used to fit the cyclic load of high-voltage bushing under the actual operating environment. The steady-state temperature of the hottest spot in the bushing insulation system and its diurnal and nighttime transient temperature variation rule are obtained by lumped RC thermal network simulation. Based on the classical ZHURKOV and CRINE combined aging model, the life variation law of 550 kV oil-SF6 bushing under the rated and over-loaded operation conditions was analyzed. In this paper, the lumped RC thermal network model suitable for the high-voltage bushing structure is proposed. The insulation life of high-voltage bushing is evaluated by combined thermal network model and classical electro-thermal aging model, which supplements the traditional bushing design method considering only steady-state rated operating conditions, and has the certain theoretical guidance for the analysis of short-term current carrying capacity and long-term aging performance of high-voltage bushing.

2. Extension of Lumped RC Heat Network under Full Bushing Model
The local RC thermal network model of casing can be deduced by analytic method. However, due to the complexity of the thermal network topology under the condition of full casing model, the solution of the analytical method is limited, and new solution method needs to be sought. In view of the advantages of MATLAB/SIMULINK toolbox in calculating the circuit transient process, following software platform is used to build the overall RC thermal network model of bushing, as shown in Figure 1.
Figure 1 is global RC heat network model of casing considering both axial and radial heat flow. The model divides the casing into three parts: the gas end of the casing, the middle flange and the oil end of the casing. The following linear assumptions exist in the global RC thermal network model of bushing: 1) the maximum temperature range of high-voltage bushing is generally between -50~150°C, and thermal conductivity of the medium inside bushing is function of temperature. Thermal conductivity of the medium in the model is used to determine the thermal resistance $R$ when the temperature is 100°C. 2) the thermal convection at the ceramic bushing-transformer oil interface at tail of high-voltage bushing, and the thermal convection at the ceramic bushing-external air interface. It is difficult to quantitatively describe thermal radiation, which is lumped into thermal resistance parameters to simplify the calculation in the thermal network. 3) the boundary conditions for temperature rise calculation are: the upper part of middle flange of bushing is placed in external environment, the boundary condition is the stable temperature $T_{a1}$, and the temperature $T_{a2}$ between the oil surface and the flange of the oil cylinder is taken into account. $T_{a2}$ should be lower than oil temperature $T_{oil}$ of the transformer considering the heat dissipation effect of the oil cylinder above the oil surface. At the same time, there are two nonlinear hypotheses: 1) total thermal resistance of convection and radiation is a function of temperature difference between the fluid and the solid interface; 2) resistivity of the guide rod in the center of the casing is related to the temperature, and the heating capacity of the guide rod is a function of the temperature. In reference [10], the calorific value of the guide rod $I^2R$ is set as $I^2R$, and the non-linear change of temperature is characterized by different values of $n$. In this paper, non-linear iterative method is proposed to calculate temperature rise of RC heat network. The FEM temperature calculation model of bushing is shown in Figure 2.

Figure 2. FEM temperature calculation model of bushing.

First of all, the non-linear iteration process for calculating the temperature rise of thermal network needs to initially determine the $R$ and $C$ values of the thermal network, and determine the ohmic loss of the guide rod in the center of the bushing and the Joule heating of the insulating medium. The resistivity of the guide rod is at 20°C, and the temperature boundary conditions at the oil end, gas end and intermediate flange of the casing are applied to calculate the sections of the global thermal network of the casing under MATLAB/SIMULINK computing environment. The temperature difference at the fluid-solid interface of the casing is determined according to the initial temperature of the node. The lumped thermal resistance $R_c$ and $R_t$ representing convection and radiation are
calculated. The temperature at the node of the guide rod is extracted and the resistivity of the guide rod is modified. After correcting parameters of thermal resistance and resistivity of the guide rod, the temperature values of each node in the thermal network are calculated again, so that the iteration calculation is carried out, and the calculation results are taken as initial values to calculate the transient temperature field. Finally, the temperature values of each node in the time $T$ are formed into an array and the temperature rise curve is drawn. $T$ is the total time value of the temperature rise process.

3. Experimental Verification of Effectiveness of Lumped RC Thermal Network Model

3.1. Experimental Study on Temperature Rise of 550KV Oil-Sf6 bushing

Temperature rise test of the 550kV oil-SF6 casing was carried out. Certain amount of the current was applied to the current-carrying guide rod in the center of the casing and the temperature rise at each key point was recorded by temperature sensor. Temperature rise at 6300A is measured at the same time. Installation of casing material and temperature sensor is shown in Figure 3.

![Figure 3. Installation of temperature measurement sensor.](image)

Temperature measurement points focus on the metal conductive parts at both ends of sleeve. It is necessary to ensure the effective contact between the sensor and temperature measurement points. At the same time, the temperature sensors are welded at different diameters of the casing core to record the temperature rise at different positions of the casing core in detail. The location and number of the temperature measuring points of the casing are shown in Figure 4.

![Figure 4. Locations of temperature measurement spots.](image)

3.2. Validation of RC Thermal Network for Calculating Bushing Transient Temperature

The lumped RC thermal network model and non-linear iteration process are used to predict the temperature changes at the key locations in the temperature rise test combined with the actual material and structure of the 550kV oil-SF6 casing. The thermal network model based on the MATLAB/SIMULINK is shown in Figure 5. Considering that the length of oil end and gas end of 550kV oil-SF6 casing is basically the same, the number of axial thermal resistance layers used at both ends is 12, the middle flange is short, and the number of axial thermal resistance layers is 6. The global thermal network in Figure 5 consists of three modules: temperature output module, heat source module and RC element module. In Figure 4, there are 26 casing temperature measuring points. The following three measuring points are emphatically analyzed: the temperature of conductive rod in oil end, the tightening ring of conductive rod at gas end and the surface of ceramic parts at oil end. In the process of casing test, the ambient temperature is 22°C. At the same time, the transformer oil in the test cylinder is heated to 80°C. Under the current carrying conditions of 5000A and 6300A, the results of thermal network simulation and test temperature rise are compared with those in Figure 6. In RC
thermal network simulation calculation, the initial temperature of oil, gas conductive rod and oil-end ceramic surface is consistent with the temperature measured by experiment, which can be achieved by setting the initial value of heat capacity in the thermal network. Figure 6 shows that there is an obvious transient temperature change trend at each measuring point of the casing when the casing carrying capacity is 5000A and 6300A, that is, the initial value rises exponentially until the stable temperature value. The simulation results of thermal network are basically the same as experimental results in the changing trend and specific values, which proves validity of the lumped RC thermal network method proposed in this paper in the calculation of transient temperature of bushing. Figure 6 shows that the temperature measurement points can only be arranged outside the casing in temperature rise test, and the temperature inside the casing core, especially at the interface between the central guide rod and the oil-immersed paper core, is difficult to measure. The current carrying capacity of the central guide rod of the actual running bushing fluctuates periodically with the change of electric load, and the ambient temperature of the bushing in the field and the oil temperature of the top layer of the transformer can not be kept constant as in laboratory environment. According to the similarity principle, the lumped RC thermal network model is applied to the transient temperature field calculation of high pressure bushing under the complex operation conditions.

![Figure 5. RC thermal networks for 550kV oil-gas bushing.](image)

![Figure 6. Comparison of temperature rising results between thermal network and test](image)
4. Application of Lumped RC Heat Network Model in Transient Temperature Calculation of High Voltage Bushing

4.1. Calculating Transient Temperature under Stepped Load Curve by Lumped RC Thermal Network Model

The environment of high pressure bushing is more complicated than the temperature rise test environment in the field. Generally, it operates under full voltage and full current condition, and the transmission power changes periodically in the range of 24 hours a day. It can fit the load of the circadian cycle through the step load curve. Firstly, the steady-state temperature distribution of bushing under the rated operating current $I_{\text{rate}}$ is discussed. By analyzing the steady-state temperature distribution of bushing, the heat-resistant grade of core insulating material and rated running state of bushing can be determined at the beginning of design. The steady-state temperature distribution of the casing depends on the thermal resistance $R$ value in the thermal network. There are two methods to calculate the steady-state temperature: 1) assigning the heat capacity $C$ to the maximum value in the thermal network; 2) setting the simulation calculation time to be large enough to extract the steady-state temperature value directly. The material performance parameters used in bushing temperature distribution simulation is shown in Table 1.

| Material type          | Heat capacity/ J/(kg·°C) | Thermal conductivity/ W/(m·°C) | Density/ kg·m$^{-3}$ |
|------------------------|---------------------------|-------------------------------|----------------------|
| Aluminum               | 896                       | 172                           | 2700                 |
| Copper                 | 385                       | 388                           | 8900                 |
| Composite sheath       | 1085                      | 1.417                         | 1150                 |
| Transformer oil        | 1650                      | 0.134                         | 880                  |
| Epoxy impregnated paper| 1574                      | 0.463                         | 1430                 |

Taking 550kV oil-SF6 casing as example, steady-state temperature distribution of the axial interface between the guide rod and core insulating material in the casing center is shown in Figure 7.

Figure 7 shows that axial steady-state temperature at the interface of the guide rod in the center of the casing transits gradually from 35°C at the gas end of the casing to 80°C at the oil end, and the peak value of temperature distribution $T_{\text{max}}$ appears in the inner part of casing core near the oil end, and the hottest temperature $T_{\text{max}}$ value of the casing under the rated capacity 5000A is 107°C, which is higher than steady-state temperature in the temperature rise test at the capacity 6300A. The temperature value is 119°C higher than the steady-state temperature value of 100°C in the temperature rise test.
rise test, because the temperature measurement point in the temperature rise test is the guide rod part of the casing immersed in the oil, and the hottest spot appears in the casing core, which can not be measured. It is proved that highest temperature value obtained in the temperature rise test is not the actual hottest spot temperature in the casing. The following is mainly to study the transient temperature change law at the hottest spot of the casing. Ignoring the load fluctuation caused by random fluctuation of load and seasonal characteristics, the actual carrying capacity of the running casing can be approximately described by 24-hour cycle $t_D$. At the same time, the cyclic load can be approximately described by step load curve, the period $t_D$ can be divided into $N$ equal time intervals, and the duration of each time interval can be described by Eq. (1):

$$\Delta t_i = t_D / N (i = 1, ..., N)$$

Each time interval $T_i (i = 1, ...,)$, corresponding carrying capacity of the inner bushing is set to $I_i (i = 1, ..., N)$. In theory, the larger the value of $N$, the closer the step load curve is to the complex case of actual casing operation. However, in order to deduce the follow-up theoretical model, the $N=1,3$ and 6 are taken to illustrate respectively. The relationship between casing carrying capacity $I$ and time $t < (0, t_D)$ in these three cases is shown in Figure 8. In the design of bushing, the current carrying capacity is treated as $N=1$, but in the actual transmission and distribution network, the load of power bushing can not be constant, so the case of $N=3$ and 6 is discussed in this paper.

![Figure 8. Stepwise-constant daily load cycle with $N=1,3,6$](image)

![Figure 9. Hot-spot temperature with daily load cycle](image)

### Table 2. Relationship between $T_{i,\alpha}$ and $I_i$ under stepwise-constant daily load cycle

| Ladder curve | Time interval (h) | Current carrying capacity (A) | Percentage of rated carrying capacity (%) | $T_{i,\alpha}$ (°C) |
|--------------|-----------------|-----------------------------|------------------------------------------|------------------|
| $N=1$        | 00-24           | 5000                        | 100                                      | 106.8            |
|              | 00-08           | 2864                        | 57                                       | 88.5             |
|              | 08-16           | 5455                        | 109                                      | 112.0            |
|              | 16-24           | 4500                        | 90                                       | 101.6            |
| $N=3$        | 00-04           | 1636                        | 33                                       | 82.5             |
|              | 04-08           | 4091                        | 82                                       | 97.8             |
|              | 08-12           | 6000                        | 120                                      | 118.8            |
|              | 12-16           | 4909                        | 98                                       | 105.8            |
| $N=6$        | 16-20           | 5727                        | 115                                      | 115.3            |
|              | 20-24           | 3273                        | 65                                       | 91.3             |

The calculation of bushing thermal field under $N=3$ and 6 load conditions belongs to the thermal transient problem, and lumped $RC$ thermal network is needed to calculate the casing transient
temperature. Bushing temperature in \( i \)th load step is proportional to \( I_i^2 \), while in \( i-1 \)th load step is proportional to \( I_{i-1}^2 \). Considering the heat capacity effect inside the casing and the heat exchange with the outside environment, there will be transient thermal process of temperature transition from initial value \( T_{i,0} \) to stable value \( T_i \). The state change process is shown in Figure 9. It shows the transient change of the hottest temperature of the casing under the ladder curve of the casing carrying capacity (except \( N=1 \)). At \( N=3 \), the minimum temperature of casing temperature was about 90 degrees, it appeared at 8 a.m., and the maximum value was about 110 degrees, it appeared at 4 p.m.. When \( N=6 \), minimum temperature of the casing temperature was about 90 degrees centigrade, which appeared at 4 o’clock in the morning. The maximum value was about 112 degrees centigrade at 8 o’clock in the evening. When the temperature of \( N=1 \) was kept at about 107 degrees centigrade day and night, the difference was mainly due to the thermal inertia effect of the inner material of the casing. At the same time, the steady-state temperature \( T_\infty \) of casing is quite different from the actual temperature \( T \). Steady-state temperature values \( T_i \) and load step current \( I_i \) under different stepped curves are listed in Table 2.

4.2. Relation between Transient Temperature Process of Bushing and Long-Term Insulation Performance under Stepped Load Curve

The long-term insulation performance of bushing mainly depends on the operation state of core insulating material[11-13]. The high voltage bushing used for power transmission in the power system usually operates under full voltage and current conditions, so the insulating material of the bushing core bears the combined aging effect of electric and thermal stress at the same time. The internal radial field strength \( E_r(r) \) of bushing insulation structure operating under AC conditions can be expressed by Eq. (2):

\[
E_r(r) = \frac{U_m(L_1 + L_2)}{2 \ln \left( \frac{r_2}{r_1} \right) r} \sqrt{\ln \left( \frac{L_2}{L_1} \right) \ln \left( \frac{r_2}{r_1} \right)}
\]

In the upper formula, \( U_m \) represents the maximum operating phase voltage when the bushing is running. \( L_1 \) and \( L_2 \) are the length of the zero layer and the ground plate of the bushing capacitor core respectively, and \( R_1 \) and \( R_2 \) are the radius of the zero layer and the ground plate of bushing capacitor core respectively. The potential and electric field distribution of 550kV oil-SF6 casing under field installation condition is calculated using the full finite element model as shown in Figure 10.

![Figure 10. On-site voltage and electric distribution of bushing](image)

Formula (2) and finite element calculations show that the radial E-field intensity of casing is \( U \)-shaped, and the maximum electric field intensity in the core is 3.38kV/mm at 317kV of the working phase voltage, which is concentrated at the interface between the core insulating material and the central guide rod. Meanwhile, RC thermal network analysis shows that the radial temperature of the casing decreases from inside to outside, so the maximum field strength \( E_{\text{max}} \) and the hottest
temperature $T_{\text{max}}$ of the casing core appear at interface between the guide rod and the core insulating material in the center of the casing. It can be seen that this is the weak link of bushing insulation, which will affect the insulation performance of bushing for a long time. Figure 11 is a comparison of internal insulation breakdown between the initial operation of a high-voltage bushing and the combined aging of electricity and heat. Figure 10 (left) is the initial operation of the bushing, and its life $LF$ can be seen as 100%, while in Figure 10 (right), the life $LF$ of the bushing can be seen as 0%.

![Figure 11. Initial operation and insulation breakdown](image)

The foregoing analysis shows that the day and night loads in the life span of high pressure casing have periodicity, and the period length is $t_D$. If there are $N$ load steps in each period, the duration of each load step $T_i$ can be calculated by formula (3). Because of the continuity of the current carrying capacity and the thermal inertia of the bushing in each loading step, the transient change of hot-test temperature $T_{\text{hot-spot}}$ occurs in the loading step. However, in order to determine the loss of insulation life of the casing in the loading step, the duration of the loading step is micro-element. In each micro-element $dt$, hottest temperature $T_{\text{hot-spot}}$ of the casing can be regarded as fixed value $T_i(t)$, which is the most important for the AC casing core. $E_{\text{max}}$ with the large field strength remains unchanged throughout the operation of the casing. Therefore, the $D_t$ element interval life loss $dLF$ of the casing in the loading step can be characterized by Eq. (3):

$$dLF = dt / L\left[E_n, T_i(t)\right]$$

Among them, $L\left[E_n, T_i(t)\right]$ is the life model of insulating material for bushing, and ZHURKOV model and CRINE model are used to discuss the following. Therefore, the loss of casing life in the time interval of load step $t_i$ is $LF_i$, which is shown in Eq. (4):

$$LF_i = \int_0^{t_i} dLF = \int_0^{t_i} \frac{dt}{L\left[E_n, T_i(t)\right]}$$

If the thermal transient process in casing under step load curve is neglected, the steady-state temperature values $T_i$ under each load step are directly applied to the calculation of casing life loss $LF_i$, because $T_i$ is a constant, it can be characterized by Eq. (5):

$$LF_{i,\infty} = \int_0^{t_D} \frac{dt}{L\left[E_n, T_i,\infty\right]} = \frac{t_D}{L\left[E_n, T_i,\infty\right]N}$$

Life loss quantities $LF_i$ ($i=1,...,N$), If the life loss of the casing reaches 100% after $K$ cycles, the inner insulation breakdown of the casing will occur, as shown in Eq. (6):

$$K \sum_{i=1}^{N} LF_i = K \sum_{i=1}^{N} \int_0^{t_i} \frac{dt}{L\left[E_n, T_i(t)\right]} = 1$$

Furthermore, the number of $t_0$ that casing can undergo circadian cycle $K$ is as follows in Eq.(7):

$$K = 1/\sum_{i=1}^{N} LF_i$$
Therefore, the casing life $L_{cyc}$ can be calculated by Eq.(8):

$$L_{cyc} = K t_0$$  \hspace{1cm} (8)

In the traditional design of casing, the current carrying capacity of the central guide rod is regarded as $N=1$. Generally, the selection of the maximum field strength $E_{\text{max}}$ and the hotspot temperature $T_{\text{hot-spot}}$ in the core of the casing can meet the requirement of safe operation for 30 years. However, irreversible damage often occurs in the insulation of the casing before the 30-year end requirement. In this paper, the classical combined aging life model-ZHURKOV and the CRINE model are used to divide it into two parts. The concrete expression is shown in Eq. (9)–(10):

$$\tau = \tau_0 e^{(\omega - \chi E)/RT}$$  \hspace{1cm} (9)

$$\tau = \alpha_{h\tau,0} \frac{T_0}{T} e^{\frac{\Delta G - \Delta F E^2/2}{\Delta T}}$$  \hspace{1cm} (10)

| Table 3. Parameters of electro-thermal aging models |
|---------------------------------|---------------------------------|--------------------------------|
| Model type | Parameter name | Parameter value |
| ZHURKOV  | $\tau_0$ (s) | $1.07 \times 10^{-10}$ |
| Model  | $\omega$ (kJ/mol) | 142 |
|  | $\chi$ (kJmm/(molkV)) | 0.447 |
|  | $R$(kJ/(Kmol)) | $8.314 \times 10^{-4}$ |
| CRINE  | $\alpha_{h\tau,0}$ (s) | $1.095 \times 10^{-8}$ |
| Model  | $\varepsilon$ (F/m) | $2.213 \times 10^{-11}$ |
|  | $\Delta G$(J) | $2.1 \times 10^{-19}$ |
|  | $T_0$(K) | 293 |
|  | $\Delta V$(m$^3$) | $3.4 \times 10^{-25}$ |

The detailed derivation process of the theoretical system of long-term life assessment of insulating media and the parameters of the classical electro-thermal aging model are referred to the research results of G. Mazzanti and Faruk Aras in reference[7]–[8]. The parameters of above-mentioned life model of insulating materials for high voltage bushing are listed in Table 3. In the design of AC high voltage bushing, the maximum radial field strength of the core is generally 3.5kV/mm, and the design value of the hottest spot temperature is 110°C under the rated operating current. By substituting the above field strength and temperature control values into formula (3)–(10), it is known that the design life $L_{cyc}$ of the bushing is 48.34 years (ZHURKOV model) and 46.94 years (CRINE model), respectively. Under above two combined aging life models, the life of the bushing is 48.34 years (ZHURKOV model) and 46.94 years (CRINE model), margins of 1.61 and 1.56. The casing is set to operate under the step load curve shown in Figure 12, and its life loss is evaluated. Through the analysis of the lumped RC thermal network mentioned above, it can be seen that the change of the hottest temperature value of casing with time is shown in Figure 12. Life loss of casing insulation material under N=3,6 two step load models is shown in Figure 12.
In order to apply above theoretical system to evaluate insulation performance of bushing, three parameters are defined as follows: $L_{100}$, $L_{100}$ and $e_{100}$, as shown in Eq. (11)~(13):

$$\Delta L_{100} = 100\left(\frac{L_{\text{cyc}} - L_{\text{cy},n}}{L_{\text{cy},n}}\right)$$  \hspace{1cm} (11)

$$\Delta L_{\infty,100} = 100\left(\frac{L_{\text{cy},\infty} - L_{\text{cy},n}}{L_{\text{cy},n}}\right)$$  \hspace{1cm} (12)

$$\Delta e_{\infty,100} = 100\left(\frac{L_{\text{cy},\infty} - L_{\text{cyc}}}{L_{\text{cyc}}}\right)$$  \hspace{1cm} (13)

Among them, $L_{100}$ denotes the relative relationship between casing life value and the rated design life value under actual operation conditions, if the sign is that the actual life of regular casing is prolonged, the life is shortened if it is negative. $L_{100}$ denotes the relative relationship between casing life value and rated design life value without considering the transient temperature change caused by the thermal inertia of casing. Table 4 shows the specific values of $L_{100}$, $L_{100}$ and $e_{100}$ under N=3,6 ladder load curves under ZHURKOV model and CRINE model.

It can be seen from the table that $L_{100}$ is greater than 0 and its value is larger, which indicates that the casing life will be greater than the design life value under the condition of considering transient temperature, that is to say, the casing life under the actual load cycle is longer than the design value. The values of $\Delta L_{\infty,100}$ are more than 0 and less than $L_{100}$, which indicates that it is conservative to evaluate the insulation life of casing by parameter $\Delta L_{\infty,100}$. The reason is that the transient temperature value is generally lower than the steady temperature value due to thermal inertia of casing under overload conditions. For ZHURKOV and CRINE aging models, considering the transient process, CRINE model is more conservative than the ZHURKOV model, while considering the steady-state temperature, the two models are similar. The reason is that the steady-state temperature values of the third and fifth load steps at N=6 are higher than the rated operating temperature of 110 degrees, and the life loss rate of ZHURKOV model at higher temperatures is higher than that of CRINE model at CRINE Model.

Table 4. Values of $\Delta L_{100}$, $\Delta L_{\infty,100}$ and $\Delta e_{\infty,100}$ under different aging models

| stair-step model | Aging model | $\Delta L_{100}$ | $\Delta L_{\infty,100}$ | $\Delta e_{\infty,100}$ |
|-----------------|-------------|-----------------|-----------------|-----------------|
| N=3             | ZHURKOV     | +147.53         | +79.34          | -27.55          |
| N=3             | CRINE       | +129.9          | +73.86          | -24.37          |
| N=6             | ZHURKOV     | +89.88          | +10.91          | -41.59          |
| N=6             | CRINE       | +81.16          | +13.14          | -37.55          |

5. Conclusions

In this paper, lumped RC thermal network model and the classical theoretical system of combined electro-thermal aging factor are improved to make it suitable for the insulation system in high voltage
bushing. The short-term overload and long-term aging performance of the 550kV oil-SF6 bushing are analyzed. The following conclusions can be drawn:

1) There are three kinds of the heat conduction modes: heat conduction, convection and radiation in the actual high-pressure casing. The lumped RC heat network model can concentrate the above heat conduction modes into the network parameters, and the transient temperature change of the casing calculated by the thermal network simulation is consistent with actual temperature rise test results, which proves that the improved RC heat network is suitable for the high-pressure casing structure and has certain effectiveness.

2) The step load curve can approximate the load cycle change in actual operation of high-voltage bushing. Transient temperature calculated by lumped RC thermal network shows that the hottest spot of high-voltage bushing is located at the interface between the central guide rod and the insulating core, and the transient temperature value of bushing is quite different from the steady temperature value under each load step. The transient temperature value can better reflect actual operation of the insulating system of bushing.

3) The classical ZHURKOV and CRINE models with combined electro-thermal aging factors are applied to analyze the long-term aging performance of the high-pressure casing. The electrical and thermal stresses are obtained by full-model finite element method and lumped RC thermal network method respectively. The results show that the casing life will be greater than the design life value under the consideration of transient temperature, and the CRINE model is more conservative than the ZHURKOV model.

4) Method used in this paper only considers the electro-thermal aging process of the insulating material and the periodic variation of the actual load. It does not take into account the failure of the insulating material caused by the internal insulation defects and mechanical vibration, but to a certain extent, gives the calculation method and theoretical explanation of the failure mechanism of the insulating material in the bushing. Therefore, the follow-up research will further extend it to the case of considering the actual insulation defects. Although there are great modeling difficulties and uncertainties, it is still a challenging research topic.

6. References

[1] Jinghan He, Le Yu, Xiaojun Wang, et al. Simulation of transient skin effect of DC railway system based on MATLAB/Simulink[J]. IEEE Transactions on Power Delivery, 2013, 28(1): 145-152.

[2] Cheng Shukang, Li Cuiping, Chai Feng. Analysis of the 3D steady temperature field of induction motors with different cooling structures in mini electric vehicles[J]. Proceedings of the CSEE, 2012, 32(30):82-90.

[3] Shibao Zhang. Evaluation of thermal transient and overload capability of high-voltage bushings with ATP[J]. IEEE Transaction on Power Delivery, 2009, 24(3):1295-1301.

[4] Ma Hongzhong, Geng Zhihui, Wang Qingyan, Zhang Zhiyan. Analysis and calculation for heating and temperature rise of magnetic levitation device[J]. Proceedings of the CSEE, 2012, 32(30):126-132.

[5] G.Mazzanti. The combination of electro-thermal stress, load cycling and thermal transients and its effects on the life of high voltage ac cables[J]. IEEE Transactions on Dielectrics and Electrical Insulation, 2009, 16(4):1168-1179.

[6] Jasmin Smajic, Jillian Hughes, et al. Numerical computation of ohmic and eddy-current winding losses of converter transformers including higher harmonics of load current[J]. IEEE Transactions on Magnetics, 2012, 48(2): 827-830.

[7] Zhang Chunyu, Li Chengrong, Han Xiaohui et al.Thyristor junction temperature estimation based on measured temperature of molybdenum flat[J]. Proceedings of the CSEE, 2012, 32(22):195-201.

[8] Merkebu Z. Degefa, Matti Lehtonen, Robert J. Millar. Comparison of air-gap thermal models for MV power cables inside unfilled conduit[J]. IEEE Transactions on Power Delivery, 2012, 27(3): 1662-1669.
[9] Merkebu Z. Degefa, Matti Lehtonen, Robert J. Millar. Comparison of air-gap thermal models for MV power cables inside unfilled conduit [J]. *IEEE Transaction on Power Delivery*, 2012, 27(3):1662-1669.

[10] Youmin Yu, Tien-Yu Tom Lee, Victor Adrian Chiriac. Compact thermal resistor-capacitor-network approach to predicting transient junction temperatures of a power amplifier module [J]. *IEEE Transaction on Components, Packaging and Manufacturing Technology*, 2012, 2(7):1172-1181.

[11] Sujit Purushothaman. Heat-transfer model for toroidal transformers [J]. *IEEE Transaction on Power Delivery*, 2012, 27(2):813-820.

[12] Miguel E. Rosillo, Carlos A. Herrera, Guillermo Jaramillo. Advanced thermal modeling and experimental performance of oil distribution transformers [J]. *IEEE Transaction on Power Delivery*, 2012, 27(4):1710-1717.

[13] Aldo Boglietti, Enrico Carpaneto, Marco Cossale, Silvio Vaschetto. Stator-winding thermal models for short-time thermal transients: Definition and validation [J]. *IEEE Transactions of Industrial Electronics*, 2016, 63(5):2713-2721.