Electro-thermal Model for Thyristor for HVDC Valve

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***Abstract*: To enhance the electricity grid's capacity of resource allocation, long-distance, large capacity (Ultra) high-voltage DC transmission technology is widely used. Significantly increased voltage and current levels affect both electric and thermal characteristics of the thyristors in a DC converter valve. This paper aims to establish a thyristor electro-thermal model to analyze the interaction between electrical and thermal stresses under various steady and transient operation conditions. Thyristor junction temperature prediction method was investigated to ensure its long-term reliability in applications.**

Keywords: UHVDC; thyristor; electro-thermal; junction temperature

I. INTRODUCTION

Presently, conventional thyristor valve technology is still widely used in HVDC systems, including long-distance transmission lines and back-to-back projects, and the capacity is still increasing. Rated voltage and current levels for the under construction Jinping to Sunan UHVDC project are ± 800kV and 4500A respectively. 7.2kV/4500A thyristor technology was proposed for this project. Meanwhile, ±1100kV UHVDC converter valve, which would set a new HVDC voltage level record, is under development.

Rising voltage and current levels not only increase the thyristor electrical stress, but also increase its thermal stress. As a silicon semiconductor device, a thyristor's thermal and electrical characteristics are interlinked and one affects the other. Running a thyristor will produce power loss at all stages of an operation cycle. The instantaneous dissipation *p* is equal to the product of voltage across and current through the device under study. However, the thyristor resistance is different for different stages of an operation cycle, so-called non-linear resistance characteristics. The voltage drop at conduction, for example, depends on the conduction current I, and is also closely related with the junction temperature T. Previous papers [1] [2] have analyzed this characteristic and some practical models were proposed.

After determining the power dissipation, the remaining work is to predict the thyristor junction temperature by studying its thermal response to a given power dissipation. Ref. [3]-[5] studied the thyristor's heat transfer characteristics, equivalent circuit models were used to represent the device's thermal structure. It was confirmed that equivalent circuit model for the steady state is quite different from that for the transient condition.

For a typical HVDC converter valve design, individual thyristors are protected using their relevant auxiliary components such as damping circuits and heatsinks. These auxiliary components are generally connected in the same cooling circuit as for the thyristor. How to deal with the electric or thermal relationships between the thyristor and its auxiliary components is another issue to consider in this paper.

II. THYRISTOR ELECTRO-THERMAL CHARACTERISTICS IN STEADY-STATE CONDITION

For convenience, thyristor heat dissipations are usually analyzed independently for different switch states in an operation cycle, including P_{ton}, P_{on}, P_{toff}, P_{off} which indicate losses produced during turn-on, on-state, turn-off, off-state respectively [6].

As soon as the thyristor losses for each individual state are obtained, the total power thyristor dissipations can be obtained by summing up individual losses and then multiplied by the system frequency as:

$$P_{total} = f(P_{ton} + P_{on} + P_{toff} + P_{off}) \qquad (1)$$

Where f represents the system frequency, which is usually 50 or 60 Hz.

At steady-state operation, the thyristor internal thermal equilibrium is reached and the thyristor junction temperature remains constant. As a thyristor includes several layers of different materials and geometries, the temperature drops inside different materials remains different [8]-[10]. For efficient cooling, thyristors are clamped between heatsinks and there are thermal contact resistances on the thyristor-heatsink interface. Besides this, the heatsinks themselves have their own thermal resistances. Therefore the total junction to ambient thermal resistance of a combined thyristor and heatsink assembly in fact includes several thermal resistances connected in series as shown in Fig.1.

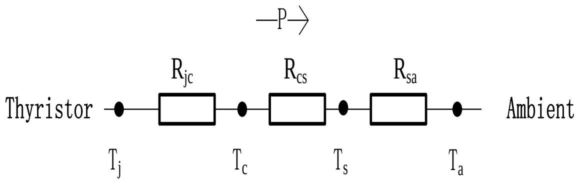

Figure 1. Thermal model of a thyristor in steady-state

Suppose that the thyristor heat dissipation spreads along one direction (Actually the bilateral dissipation spread case could be simplified to a single direction one), the thyristor junction temperature can be expressed as follows

$$T_j = T_a + P(R_{jc} + R_{cs} + R_{sa}) \qquad (2)$$

Where *T*, *P*, *R* indicate temperature, power dissipation and thermal resistance respectively. And the subscripts *j*, *c*, *s* and *a* represent the thyristor junction, case, heatsink and ambient respectively.

III. TRANSIENT ELECTRO-THERMAL CHARACTERISITCS

A. Ttransient dissipation analysis

In the transient conditions, the junction temperature is no longer constant. A typical example is when there is a flashover across a converter valve, the valve thyristors will experience a short pulse of fault current of great amplitude which leads to a rapid rise of the thyristor junction temperature, and consequently diminished voltage withstand capability. It is therefore necessary to take full account of the thyristor junction temperature and limit it within a safe range at the design stage of a HVDC scheme.

During the transient time, thyristor on-state voltage drop is not merely related to the conduction current, but also dependent on the transient junction temperature. The dependency can be expressed by a function v = f (i, T) as explained in full details in Ref. [2]. The function is described in this paper by utilizing a new concept COD:

$$COD = \frac{\Delta V_T}{(T_j - 25°C)} \qquad (3)$$

Where ΔV_T is the change of on-state voltage at a particular current I_T, T_j is the temperature change from any designated reference, e.g., 25℃. So at I_T and T_j, the on-state voltage can be expressed as

$$V_T = V_{ISO} + COD(T_j - 25°C) \qquad (4)$$

Where V_{ISO} is the value of V_T at any reference temperature, e.g., T_{REF}=25℃. V_T could be determined as long as the value of COD is known. According to [2], the COD value can be expressed by an equation as following, which was obtained by fitting experimental data for a particular type of thyristor.

$$COD = [K(\frac{I_T}{I_{REF}}) + (\frac{T_j}{100})^n](\frac{I_T}{I_{REF}})^p \qquad (5)$$

After the voltage dependence of I_T and T_j is obtained, the on-state power dissipation could be calculated using

$$P = V_T I_T = [V_{ISO} + COD(T_j - 25)]I_t = F(I_T, T_j) \qquad (6)$$

Which indicate that the instantaneous thyristor power dissipation can be a function of I_t and T_j, $F(I_T, T_j)$.

B. Transient thermal characteristics

To calculate the thyristor transient temperature excursion, it needs not only to know the instantaneous losses of the thyristor, but also the device's transient thermal characteristics. Some of the early literatures show that thyristor transient thermal characteristics could be described using equivalent RC circuits. Among all different simulation models, Foster and Cauer models were mostly cited, see Fig.2 and Fig.3 for details. In the figures, the thyristor power dissipation is represented using an excitation current of equal amplitude P(t). Node voltage T_1 represents thyristor junction temperature T_j, Ta for the ambient temperature, r_i and c_i (i=1,2,n) are the thermal resistances and thermal capacitances of the device and its relevant cooling elements.

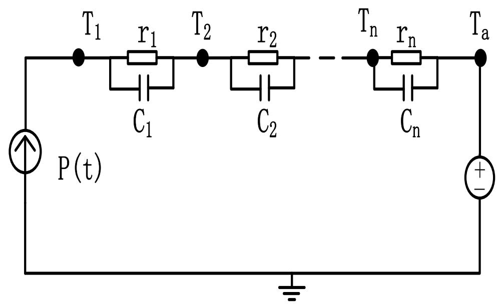

Figure 2. Foster network

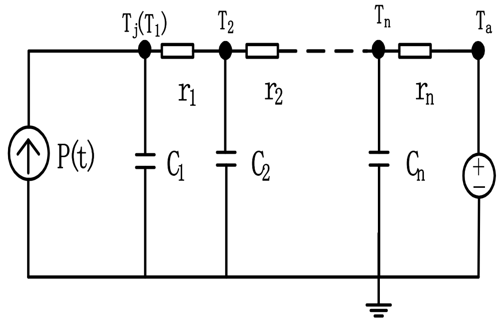

Figure 3. Cauer network

Using the above models, thyristor junction temperature excursion T_j for any arbitrary power dissipation can be obtained. Fortunately, the transient thermal characteristic of a device is generally available from the manufacturer datasheets, as shown in Fig.4.

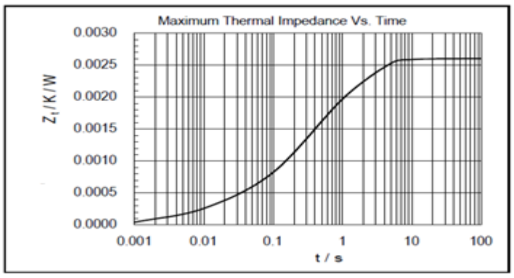

Figure 4. Transient thermal impedance

Transient thermal impedance curve can be fitted [7] by a set of exponential functions as

$$Z_t = \sum_i R_i (1 - e^{-\frac{t}{\tau_i}}) \tag{7}$$

As the Foster equivalent circuit's step response is most similar to that for Z_t, it makes sense to obtain the thermal parameters by fitting the manufacture Z_t data using the Foster model by assuming

$$r_i = R_i, c_i = \frac{\tau_i}{R_i} \tag{8}$$

The simulation error will be relatively large if the same Z_t data is represented using the Cauer model. Instead, an accurate Cauer model can be obtained indirectly from the Foster model, because the two models have the same Laplace complex impedance, Z_f and Z_c.

$$Z_f = Z_c \tag{9}$$

Where

$$Z_f = \sum_i \frac{R_i}{s(1 + s\tau_i)}$$

$$Z_c = \cfrac{1}{sC_1 + \cfrac{1}{R_1 + \cfrac{1}{sC_2 + \cfrac{1}{R_2 + \cfrac{1}{sC_3 + \dots + \cfrac{1}{R_n}}}}}}$$

Although it is not straight forward to obtain the Cauer model from a set of Z_t data, it has clear physical meaning. In the Foster network, node voltage T_1 represents the device's junction temperature, but the rest of the node voltages, such as T_2 and T_n have no practical significance. However in the Cauer network, node voltage T_i (i = 1, 2, ... n) represents temperatures of particular joints of a cooling path.

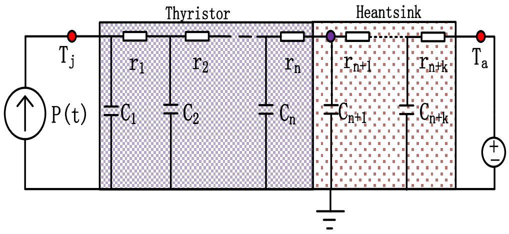

Figure 5. Equivalent thermal impedance circuit of a thyristor with heatsink

High power thyristors of an actual HVDC valve structure, for example, are typically sandwiched between two water-cooled heatsinks. The overall thermal properties of the combined thyristor and heatsinks could be demonstrated using a thyristor Cauer model cascaded with a heatsink Cauer model as shown in Fig. 5.

C. Transient thyristor junction temperature calculation

After power dissipation P and equivalent thermal impedance model for a given device are determined, junction temperature of the device could be established by applying the power dissipation to the equivalent thermal impedance model. Iterated calculations are required considering the dependence of power dissipation on thyristor junction temperature.

IV. CALCULATION RESULTS

Fig. 6 and Fig. 7 give the numerical results for the junction temperature excursions for the one-loop and three-loop fault current conditions for a typical 12-pulse HVDC converter design [8]. Amplitude of the fault current is set at 50kA, and the assumed duration is 17.8 milliseconds.

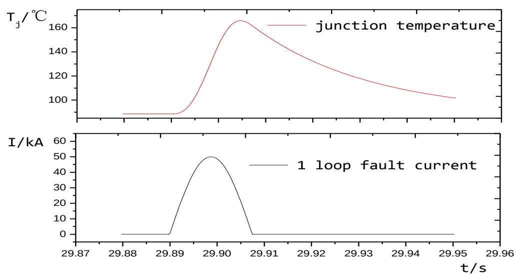

Figure 6. T_j for single-loop fault current

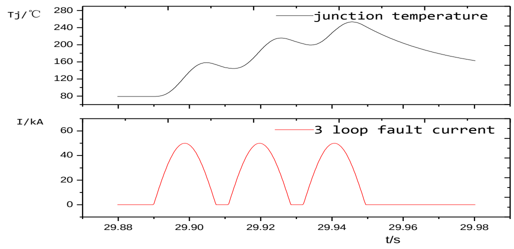

Figure 7. T_j for a 3-loop fault current

V. CONCLUSION

Steady and transient state thyristor junction temperatures could be obtained by solving the equivalent thermal impedance circuit for respective power dissipation excitations. Accurate prediction of the thyristor transient junction temperature depends greatly on accurate extraction of the parameters for the relevant thermal model, including the COD expression parameters and the equivalent thermal impedance circuit.

In fact, the equivalent circuit method described in this paper simplifies a 3-D thermal conduction question as a 1-D one. The obtained results represent only the maximum junction temperature of a thyristor. The simulation result using this simplified method is sufficient for protecting the power devices in actual applications, especially considering that direct measurement of the junction temperature is almost impossible.

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