Research on Reliability Assessment of Thyristor in HVDC Converter Valve

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Abstract: With the development of HVDC transmission technology, the efficiency and reliability of the operation of the converter valve have been widely concerned. Because the core device of the converter valve is thyristor, safe and effective operation of the thyristor is the prerequisite for efficient operation of the converter valve. In this paper, the thermal impedance model is established according to the radial heat dissipation direction of the thyristor. The basic electric heating correspondence is used to describe the rate of heat rise per unit time by the rate of change of the heat capacity temperature at each node. Through simulations and calculations, the heat change of each part of the thyristor during converter valve is in operation is analyzed, and the parts where the thyristor of the converter valve is easily damaged are analyzed. This method takes the influence of temperature on thyristor into consideration and provides a new angle to describe the reliability of the operation of thyristor.

1. INTRODUCTION

Long distance power transmission should be realized at low current and high voltage. During the long distance power transmission of alternating current, voltage class should be improved by transformer to ensure the transmission.¹ However, there are around 10 percent losses in the pressurization process of transformer. In order to decrease the losses produced by alternating current in long distance power transmission, the applications of direct current transmission are wider than ever. People pay more attention to ensure the safety in operations of converter valve. The system of HVDC transmission consists of rectifier station, inverter station, transmission line and AC power system. The rectifier station transforms alternating current into direct current. The current flows through transmission line and inverter station transforms direct current into alternating current. Two power systems with different
frequency and phase can be combined by DC transmission line to solve the closing problems of power systems with different frequency.

Thyristor is the core device in HVDC converter valve and the persistence of converter valve depends on the reliability of thyristor. Internal structure of thyristor consists of 3 different P-N junctions, which is $P_1-N_1-P_2-N_2$ structure. When P-N junction gets a balance between multi-sub-diffusion and minority drift, the space barrier zone will form and P-N junction can be regarded as capacity.

Whether it is stationary or overvoltage, the operation of converter valve will be influenced with damage of P-N junctions. Thyristor consists of 3 different P-N junctions, $J_1$, $J_2$ and $J_3$. When the thyristor is conducting, $J_1$ and $J_3$ are forward biased and $J_2$ is reverse biased; when the thyristor is reversed, $J_1$ and $J_3$ are reverse biased and $J_2$ is forward biased. A voltage surge or an increase in temperature does not completely destroy the P-N junction in some cases, but at this time the thyristor has been damaged, which will affect the life and reliability of the converter valve. Through the thermal model construction, the P-N junction inside the thyristor is replaced by multiple parallel equivalent capacitors. If the change of the capacitance voltage changing rate inside the thyristor can be realized, the life and reliability of the converter valve can be improved, even to provide some ideas for online monitoring.

2. Research Background and Failure Mechanism Analysis of HVDC Converter Valve Reliability

From the point of view of mechanical deformation, a method for evaluating the life of thyristors is one-way and can only be used to analyze the one-way deformations when external force is applied. For the crimp thyristor, in the extreme over-voltage environment, due to the different thermal expansion coefficients of different materials at the crimping gap, when the internal temperature of the thyristor rises, the degree of expansion of different materials is different, and cracks may occur. The deformation at this time is not one-way. The main direction is along the crimping line, and there may be subtle cracks. At this time, the method in the literature cannot handle such a complicated situation [1].

Taking the six-pulse converter valve as an example, the failure mechanism of the converter valve under overcurrent conditions is introduced. Because of the commutation reactance and parasitic inductance of the thyristor, the thyristor has commutating teeth in the commutation process. For example, $V_1$ and $V_6$ are the thyristors currently working. $V_1$ and $V_6$ commutates to $V_1$ and $V_2$ for phase change, at this moment, $V_2$ and $V_6$ will be turned on at the same time. And then B and C are short-circuited in two phases, which generates a huge short-circuit current and is harmful to the converter valve, bringing different kinds of losses. However, the drawback of this document is that no effective solutions have been proposed to limit overcurrent hazards [2].

![Figure 1 Six-pulse bridge type converter valve](image)

The commutating teeth can raise the voltage significantly, so that the commutation zero of the thyristor comes earlier. For the inverter station in the HVDC transmission line, the thyristor commutation failure may be caused. This problem will increase the reactive power consumed and the harmonic current in the circuit. In this situation, operations of the converter valve are adversely affected [2].

Taking the six-pulse converter as the research object, when $V1$ is faulty and short-circuited, $V_3$ is subjected to reverse voltage so that it is turned off. This text regards short-circuit condition as instantaneous zero-state response. The second-order differential circuit model is used to set the damping parameter and to simulate the effects of different parameters on the shutdown voltage, analyzing a number of angles[3].

For the difference of junction temperature of thyristor components in series waterway, a calculation
equivalent model of junction temperature of thyristor of valve assembly is established. Seven thyristors are connected in series, and the waterway is constructed according to the method of half-face heat dissipation. This structure can measure the highest temperature Tmax accurately. The temperature rise is calculated through using the heat taken away by the water per minute. This method subtly combines the water cooling system with the thyristor valves and uses PLECS to calculate the final junction temperature. However, this method also has some problems. Firstly, the applicable range is very narrow. Secondly, this method is only for a specific circuit and lacks universality. Moreover, thyristor half-face heat dissipation model cannot guarantee that the water cooling system covers completely in practice. A series of problems such as water impurities and the calculation formula may cause errors in experiments.

Overcurrent and overvoltage have a great influence on the reliability of the converter valve’s thyristor. Firstly, the Si layer of the thyristor acts as the main heat-generating layer where the thermal conductivity is low. The heat generated by Si layer is diffused to the Mo layer and the Cu layer partly. The heat build-up causes the junction temperature to rise, which easily causes damage to the P-N junction. Secondly, when the thyristor is turned off and UKA is too high, the thyristor will avalanche breakdown, so that the holes inside P1 will increase and the electronics inside N2 will increase. However, they will not recombine after moving so that a huge voltage and an overcurrent damage will be brought to thyristor. Finally, the current has a self-heating effect. When the thyristor is turned on, current flowing through the thyristor will increase the thyristor resistance and the conduction loss. With the losses increasing, the junction temperature of the thyristor rises, which may damage the thyristor.

In order to reduce the damage probability of thyristor, it is necessary to establish a life evaluation model. In this paper, the thermal impedance model is established along the radial heat dissipation direction of the thyristor, which uses the electric heating correspondence. Voltage of the capacity corresponds to temperature rise of the heat capacity. The heat capacity represents the temperature rising relationship with the time. The larger the heat capacity, the faster the temperature rises per unit time. From the angle of the physical processes, the voltage rise of capacity is similar to the temperature rise of heat capacity. The changing rate of the capacity’s voltage can correspond to the changing rate of heat capacity’s temperature rise. The changing rate of heat capacity’s temperature rise mainly reflects the rise of the temperature on the heat capacity per unit time. Under different excitation sources, the larger the parameter, the higher the temperature rises per unit time. The rising rate is large and the effect on the efficiency and stability of the converter valve is higher. In this paper, we use the known thermal resistance and heat capacity parameters to establish the "T" type circuit and Cauer circuit model according to the heat dissipation direction. Through establishing a recursive relationship, this text uses PLECS to simulate these circuits and calculates the temperature rising rate at different nodes. The temperature rise of thyristor is dynamically monitored under the source to determine the safe operation of thyristor.

3. Thermal impedance modeling of thyristor heating layer Si sheet and calculation of heat capacity temperature rising rate under stable working conditions

Under the condition that thyristor is in normal operation, the Cauer model can be used to establish thermal impedance model of the thyristor. However, internal structure of the thyristor is divided into a heat generating layer which can be considered as Si layer and a non-heat generating layer including Mo layer, Cu layer and heat-sink. There are ceramic layers attached to both sides. Therefore, for the heat-generating Si layer, the "T" type circuit can be used to model the thermal resistance circuit. The heat generation of entire thyristor is in the Si layer, so the power current source P(t) can be equally divided into n parts so that each module can uniformly heat up.

![Figure 2 Thermal Si film thermal impedance model](image-url)
This text takes B as the zero potential reference point. From the left, the positive value of the first capacity is 1 and the second to the right is 2, and so on. It is possible to set a total of n nodes. Write KCL equations for each capacitor node,

\[ \frac{P(t)}{n} = i_1 + i_{C_1}; \]  
\[ \frac{P(t)}{n} + i_1 = i_2 + i_{C_2}; \]  
\[ \frac{P(t)}{n} + i_2 = i_3 + i_{C_3}; \]  
\[ \vdots \]  
\[ \frac{P(t)}{n} + i_{n-1} = i_n + i_{C_n}; \]  
\[ i_n = C \frac{du_{C_n}}{dt} = CK_n; \]

Add the above n expressions to get

\[ P(t) = i_n + C(K_1 + K_2 + \cdots + K_n); \]

In the above formula, \( P(t) \) is the power source, \( i_n \) is the heat flow at the n-node, and \( K_n \) is the heat capacity temperature rising rate at the n-node.

Through the electro-thermal conversion diagram shown in the above figure, the estimation method of junction temperature is proposed. After the node voltage of each part is obtained, the corresponding junction temperature data can be found by checking the thyristor technical manual and the simulation is performed by using PLECS. The heat flow images of different nodes are made to calculate the heat capacity voltage changing rate of different nodes [5].

| Thermal resistance (K/kW) | Thermal resistance in each part (K/kW) | Thermal resistance in each part of “T” type circuit (K/kW) | Thermal capacity (J/K) | Thermal capacity in each part (J/K) |
|--------------------------|-------------------------------------|-------------------------------------------------|----------------------|-----------------------------------|
| 0.19                     | 0.0475                              | 0.02375                                         | 35.6                 | 8.9                               |

Figure 3 "T" type thermal resistance circuit test chart when n=4
Figure 4 The waveform of $i_1$ when $n=4$

Figure 5 The waveform of $i_2$ when $n=4$

Figure 6 The waveform of $i_3$ when $n=4$
Through the above simulation and formula calculation, the whole thyristor is heated under action of excitation source. Except for the first heat capacity, the temperature rise of heat capacities decreases one by one. However, with increase of the value of power sources, the extents of temperature decrease on following capacities are not obvious. The heat generation of the excitation source and the subsequent heat capacity increase the junction temperature of thyristor. From an electrical point of view, it is equivalent to a capacitor discharge which releases the capacitor current, even if the $i_c$ is very small. The first heat capacity’s temperature rise is much larger than the latter heat capacities, so voltage of first capacity in the circuit rises the fastest. The first capacity withstands the highest voltage and is most likely to be broken down, requiring special attentions and protections.

According to the calculation of the basic circuit when $n=4$, this text measures the heat flow $i_k$ and calculates the heat capacity temperature rising rate $K$ of each node when $n=8$. Under the condition of different segment number $n$, the reliability of whole thyristor can be based on this assessment.

**Table 2 Measurement of $i$ and calculation of $K$ when $n=8$**

| P(t) | 4kW | 8kW | 12kW | 16kW |
|------|-----|-----|------|------|
| $i_4$ | 1.7 | 2.03 | 3.5 | 6.7 |
| $k_4$ | 0.0191 | 0.142 | 0.234 | 0.2693 |
| $i_3$ | 0.87 | 1.3 | 2.6 | 5.1 |
| $k_3$ | 0.0573 | 0.17 | 0.236 | 0.2586 |
| $i_2$ | 0.38 | 0.81 | 1.7 | 3.4 |
| $k_2$ | 0.0832 | 0.177 | 0.243 | 0.259 |
| $i_1$ | 0.12 | 0.39 | 0.87 | 1.7 |
| $k_1$ | 0.0988 | 0.181 | 0.24 | 0.258 |

**Table 3 Si thermal resistance circuit parameters when $n=8$**

| Thermal resistance (K/kW) | Thermal resistance in each part (K/kW) | Thermal resistance in each part of “T” type circuit (K/kW) | Thermal capacity (J/K) | Thermal capacity in each part (J/K) |
|---------------------------|----------------------------------------|----------------------------------------------------------|------------------------|-----------------------------------|
| 0.19                      | 0.02375                                | 0.011875                                                 | 36.5                   | 4.5625                            |

**Table 4 Measurement of $i$ and calculation of $K$ when $n=8$**

| P(t) | 8KW | 16KW | 24KW | 32KW |
|------|-----|------|------|------|

The bigger the $n$ becomes, the higher the accuracy of the description of the circuit describes.

4. Thermal resistance modeling of non-heating layers including Mo, Cu and heat-sink and calculation of capacitance voltage changing rate

This section mainly describes the modeling of the Mo layer and the Cu layer in the non-heating layer, and uses the recursive formula to calculate the thermal parameters.

![Thermal resistance model structure diagram of Mo layer and Cu layer](image)

Add the excitation source to the port. If the node number closest to the excitation source is 1, you may wish to set a total of $n$ nodes.

\[
P(t) = C \frac{dU_{C1}}{dt} + i_1;
\]

\[
i_1 = C \frac{dU_{C2}}{dt} + i_2;
\]

\[
i_2 = C \frac{dU_{C3}}{dt} + i_3;
\]

\[
\ldots
\]

\[
i_{n-1} = C \frac{dU_{Cn}}{dt} + i_n;
\]

Add the above $n$ expressions to get

\[
P(t) = i_n + C(K_1 + K_2 + \ldots + K_n);
\]

**Table 5 Thermal resistance circuit parameters of Mo and Cu when n=4**

| Thermal resistance (K/kW) | Thermal capacity (J/K) | Thermal resistance in each section (K/kW) | Thermal capacity in each section (J/K) |
|--------------------------|------------------------|------------------------------------------|----------------------------------------|
| 1.89                     | 135                    | 0.4725                                   | 33.75                                  |

When different materials are brought together, contact resistance is generated and contact resistance is generated at the Si-Mo junction and the Mo-Cu junction. The thermal model of the Mo and Cu layers was established through using the Cauer model along the direction of heat dissipation from the thyristors.

Add the above $n$ expressions to get
Figure 10 Plate thermal impedance model of Mo and Cu when n=4

| P(t) | 5KW   | 10KW  | 20KW  | 30KW  |
|------|-------|-------|-------|-------|
| i₁   | 0.295 | 0.59  | 1.2   | 1.78  |
| K₁   | 0.1394| 0.2788| 0.557 | 0.836 |
| i₂   | 0.009 | 0.018 | 0.036 | 0.054 |
| K₂   | 0.0085| 0.017 | 0.034 | 0.0513|
| i₃   | \    | \    | \    | \    |
| K₃   | 0.0085| 0.017 | 0.034 | 0.0513|
| i₄   | \    | \    | \    | \    |
| K₄   | 0.0085| 0.017 | 0.034 | 0.0513|

It can be obtained from the calculations and simulation results. From the electrical analysis, the first capacity of whole model has the highest withstand voltage, also representing the highest temperature rise on first heat capacity. The position closest to the excitation source suffers from the highest impact, which is the most vulnerable. Starting from the third node, the heat flow of the flow superheat resistor is basically 1% of i₂, which can be negligible. Except for the first heat capacity, the temperature rise of other heat capacities is basically the same, which means that the corresponding capacity’s voltage rises is similar.

5. CONCLUSION

By comparing and calculating the temperature changing rate of the above-mentioned Si layer, Mo layer and Cu layer, according to the equivalent model, the heating temperature rise of the Si layer is mainly derived from the exothermic heat of some heat capacities and the power source of each section. The temperature rise of the Mo layer and the Cu layer is not as obvious as that of the Si layer and the temperature is mainly raised by the heat conducted from the Si layer. Since the common point of the two models is that the temperature rise is the highest near the heat source and the corresponding voltage breakdown rate is large, which is easy to damage the thyristor. Corresponding to the thyristor’s structure, it can be known from the calculation that the thyristor center of Si piece, Si-Mo junction and the Mo-Cu junction is the most susceptible to damage. Corresponding to the nature of material, due to the different thermal expansion coefficients of different materials at the junction, when there is a large temperature rise, the degree of expansion of different materials is different, which is easy to cause damage to the thyristor. Regardless of the Si layer, the Mo layer or the Cu layer, the temperature rise of the heat capacity during the heat transfer process is basically gradually decreasing, but the temperature rise of the position closest to the heat source is the highest.

For the thyristor structure inside the HVDC converter valve, it is necessary to pay attention to the electric shock and heat change of the thyristor at the time of operation. The analysis method proposed in this paper is only to analyze the change of heat in different levels of the thyristor under transient conditions and junction temperature of thyristor. Real-time monitoring requires further researches and organizations.

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Reference

[1] Liang N, Zhang Z.G, Liu C. 2018. Failure Mechanism Analysis and Physics-of-Failure Lifetime Prediction Method for Press-pack Thyristor of Converter Valve in EMP Environment. In: The 2018 International Power Electronics Conference. Niigata, pp. 1157-1161.

[2] Xie T, Zha K.P. (2010) Study on Failure Mechanism of HVDC Valve Caused by Overcurrent in UHVDC Power Transmission Devices. Power System Technology, 10: 71-75.

[3] Xie T, Tang G.F, Zheng J.C. (2012) Analysis on Reverse Voltage Characteristics of HVDC Thyristor in the Fault State. Proceedings of the CSEE. 1:140-146.

[4] Zhang J.B, Huang H, Zhang X. (2017) Calculation Research of Thyristor’s Junction Temperature with High Voltage Direct Current Converter Valve. Electrotechnics Electric, 8:24-26

[5] Yang J, Tang G.F. (2013) Study on Equivalent Circuit Model for HVDC Valve Thyristor Junction Temperature Calculation. Proceedings of the CSEE. 15:156-163