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Transient Temperature Field Analysis of Thyristor Turn-on Process under Narrow Pulse Width and Large Current

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Abstract. Thyristor will damage because of local overheating under narrow pulse width and large inrush current, if the selection is unreasonable. In this paper, the thermal field model of thyristor opening process is established and the transient temperature field distribution of thyristor is obtained by simulation. Simulation results show that under the narrow pulse width and large current, the temperature distribution on the silicon chip is not uniform, the temperature at the center gate is the highest, and the temperature is gradually decreased from the center point along the radius. The effect of current rise rate and chip radius on thyristor temperature distribution are simulated. Simulation results show that the higher the current rise rate, the higher the temperature of the thyristor center gate. The effect of chip radius on thyristor temperature is related to the pulse width of large inrush current. When the chip radius is smaller than the extended radius corresponding to the current pulse width, the smaller the radius, the higher the maximum temperature rise. When the radius of the chip is equal to or greater than the extended radius corresponding to the current pulse width, increasing the radius of the chip has no effect on the highest temperature rise.

1. Introduction

Hybrid fast DC current limiting circuit breakers with thyristor forced-off technology require thyristors to withstand large values ($>20\text{kA}$), high di/dt ($>200\text{A}/\mu\text{s}$), and narrow pulse widths ($200\mu\text{s}$) pulse current under extreme short-circuit inrush currents [1-3].

Experiments have shown that if the thyristor tends to suffer from local overheating breakdown damage under narrow pulse width and large inrush current, if the selection is unreasonable. The reason is that the opening process of the thyristor is a process in which the current gradually expands from the gate to the cathode. It usually takes about $100\sim 200\mu\text{s}$ for the carrier to extend 1cm in length [4-6]. If the opening speed of the thyristor cannot keep up with the rising speed of the current, it will cause a very high current density in the vicinity of the gate of the thyristor, and the generated power will cause a rapid rise in temperature in the small conduction area of the thyristor, which in turn will causes damage to the thyristors [7, 8].

In this paper, the thermal conduction model of the thyristor opening process is established. The transient temperature field distribution of the thyristor during the opening process of the narrow pulse width and large current is simulated, and the influence of changing the current rising rate and the



radius of the thyristor on the highest temperature rise is discussed. These provide the basis for device selection and economic rationalization.

2. Thermal model of thyristor opening process

2.1. Thyristor heat transfer process

In this paper, the one-shot gate thyristor module is taken as a research object, and its heat transfer process is modeled and analyzed. The three-dimensional model is shown in Figure 1. The relevant parameters are shown in Table 1.

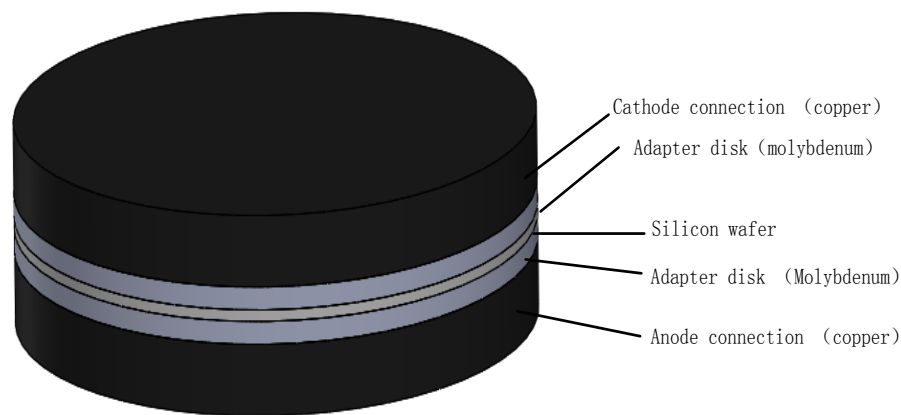


Fig. 1 The thriystor model

Tab. 1 Main paraments of thyristor

Material name	thickness /mm	diameter /mm
Silicon wafer	0.4	35
Anion/anode molybdenum sheet	1.5	35
Anion/anode copper	7.5	35

In order to facilitate calculation and analysis combined with actual working conditions, the following assumptions are made:

(1) The heating effect of the pulse current on the thyristor is only on the silicon wafer.

(2) The heating time of the pulse current to the thyristor is several hundred microseconds, And only the heat conduction inside the heat sink of the thyristor device is considered, And heat exchange between the base and the surrounding air is ignored, And the heat lost from the silicon wafer inside the thyristor from the side of the silicon wafer, the molybdenum sheet and the copper base is ignored [9, 10].

(3) The initial temperature of the thyristor is set to 273.15K

According to the theory of heat conduction, the thermal differential equation of the temperature field $T(x, y, z, t)$ inside the solid medium of the thyristor can be expressed as:

$$\text{div}(\lambda \nabla T) + q = \rho c \frac{\partial T}{\partial t} \quad (1)$$

Where T is the temperature field; t is the time; λ is the medium thermal conductivity; ρ is the medium density; c is the medium specific heat capacity; q is the heat source, which indicates the heat loss generated by the pulse current flowing through the silicon wafer. Based on Hypothesis 1, there is no current injection for copper and molybdenum sheets, and then $q = 0$.

Based on Hypothesis 2, the cylindrical surface of the entire model is an adiabatic surface, so it can be described by a second type of boundary condition, ie

$$\frac{\partial T}{\partial n} = 0 \quad (2)$$

Where n is the normal direction of the contact surface.

Based on hypothesis 3, initial conditions of thyristors is

$$T(x, y, z, 0) = 273.15K \quad (3)$$

2.2. Thyristor power density uneven distribution

The diffusion of current on the silicon wafer results in uneven heat distribution in the chip. The thermal power consumption is different at different positions on the silicon wafer at different times, and the thermal power density is different at the same position at different times. Therefore, it is necessary to analyze and treat the heat source according to the thyristor opening and diffusion process. The thyristor diffuses from the open area of the gate to both sides [11], and the diffusion process is shown in Fig.2.

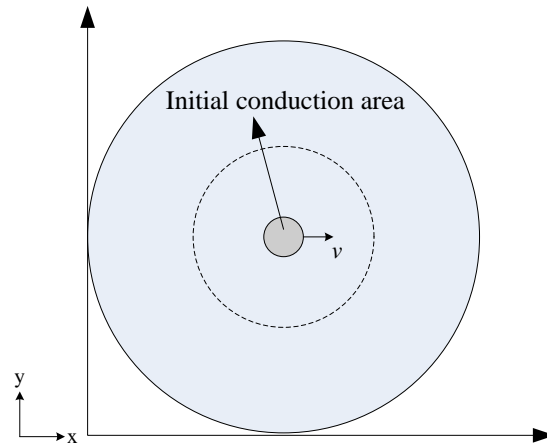


Fig.2 Thriystor turn-on process

It is assumed that the current diffusion speed is constant. The diffusion radius of the open region on the silicon wafer at any time t is:

$$W(r, t) = \frac{|r_0 + vt - r| + (r_0 + vt - r)}{2|r_0 + vt - r|} g v(t) \quad (4)$$

Where, r_0 is the initial opening area radius; v is the current diffusion speed. The opening area volume is:

$$V(t) = \pi(r_0 + vt)^2 gh \quad (5)$$

Where, h is the thickness of the thyristor wafer.

If the current density distribution of the opened region is uniform, the power density that has been turned on is:

$$w(t) = \frac{P(t)}{V(t)} \quad (6)$$

Where, $P(t)$ is the thermal power dissipation on the silicon

Experiments show that the slope resistance of the thyristor changes with the turn-on process of the thyristor, and the amplitude changes from large to small and finally tends to be constant, which is similar to the time-varying resistance^[12-16]. Take a single gate thyristor of diameter of 40mm as an example, the slope resistance can be expressed as:

$$R_T(t) = \begin{cases} 0.3247e^{-1.935 \times 10^5 t} + 0.02793e^{-2.463 \times 10^4 t} & 0 < t < 170 \mu s \\ 0.0015 & t > 170 \mu s \end{cases} \quad (7)$$

At a given current, the power on the thyristor silicon is:

$$P(t) = I^2 R_T(t) \quad (8)$$

For any point of the silicon wafer, when the open region does not diffuse to this point, the power dissipated at this point is 0; when the open region is diffused to this point, the power density here is $w(t)$. Then the power density $W(r, t)$ at any point on the silicon wafer at a radius r can be expressed as the following function:

$$W(r, t) = \frac{|r_0 + vt - r| + (r_0 + vt - r)}{2|r_0 + vt - r|} gw(t) \quad (9)$$

Using the unevenly distributed dissipated power density as a heat source q for the silicon wafer [9].

3. Simulation study

The thyristor with a radius of 20mm was simulated by COMSOL Multiphysics software, and the transient temperature field distribution of the thyristor was obtained. Figure 3 shows the current waveform injected to the thyristor, which is sinusoidal half-wave current with a rise rate of 200A/ μ s, a peak of 20kA, and a pulse width of 200 μ s. Figure 4 shows temperature distribution of the thyristor silicon chip under the current working condition. The figure selects six time nodes from 0 μ s to 200 μ s, showing the temperature field distribution during the thyristor turn-on process. Figure 5 shows the distribution of the temperature profile from the radial direction of the center of the thyristor silicon chip. This figure more intuitively reflects the effect of the expansion of the current at the thyristor silicon chip on the temperature distribution. The simulation results show that during the turn-on process of the thyristor, the temperature at the center point is the highest, and the temperature from the center point to the radius gradually decreases. This is the reason why the thyristor has a thermal breakdown at the center gate under high di/dt current conditions.

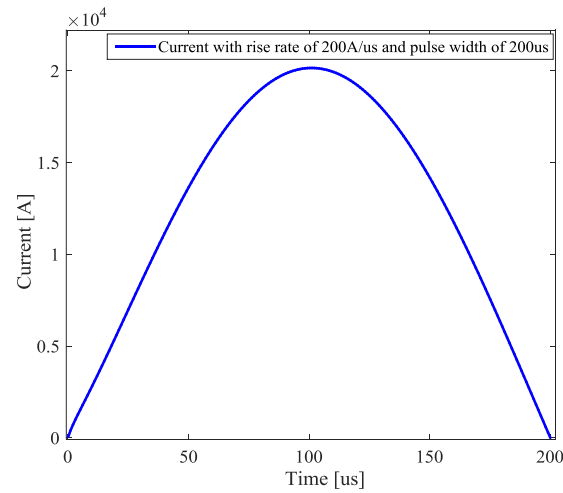


Fig.3 current waveform injected to the thyristor

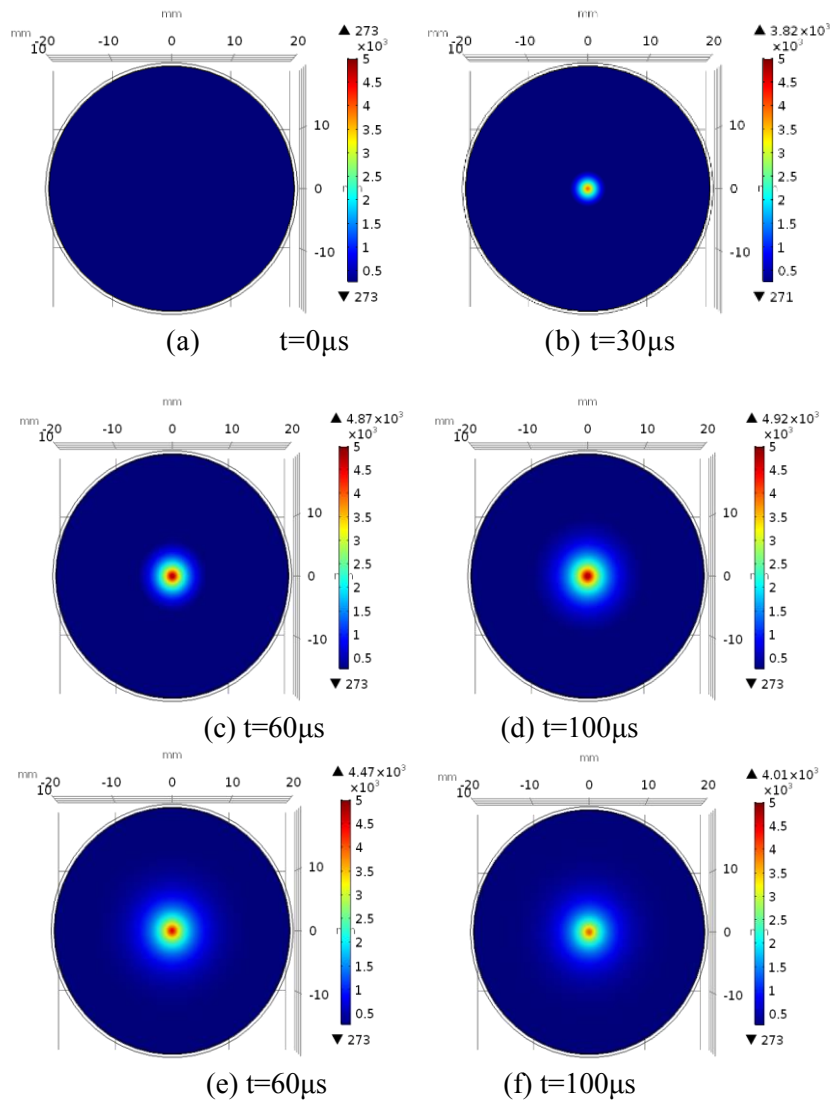


Fig.4 Temperature distribution of the thyristor silicon chip

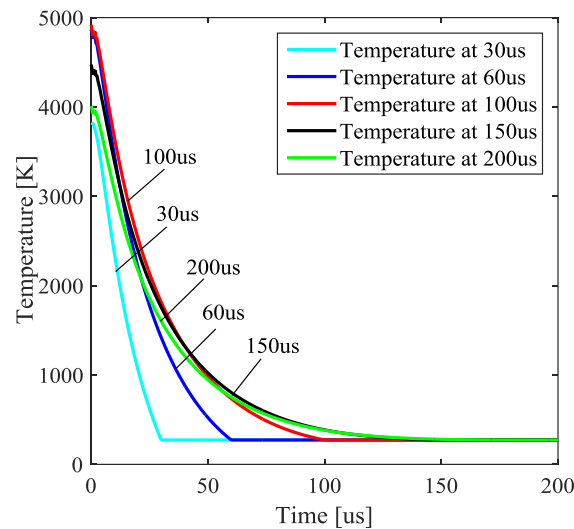


Fig. 5 The distribution of the temperature profile from the radial direction of the center of the thyristor silicon chip

4. Effect of current rise rate and chip radius on temperature field distribution

4.1. Effect of current rise rate on temperature field distribution

In order to investigate the influence of the current rise rate di/dt of the external circuit on the transient temperature field distribution during the thyristor turn-on, on the premise that the current peak is constant, a method of changing the pulse width of the sinusoidal half-wave current to change the average current rise rate is adopted. In this section, under the current peak of 20kA, the pulse width of the sinusoidal half-wave current is 400 μ s, 200 μ s and 135 μ s respectively, and the corresponding average current rise rate di/dt is 100A/ μ s, 200A/ μ s, 300A/ μ s respectively, as shown in Figure 6. The thermal field simulation of a single gate thyristor with a radius of 20mm is carried out. The highest temperature distribution curve of the thyristor at different current rise rates is shown in Figure 7.

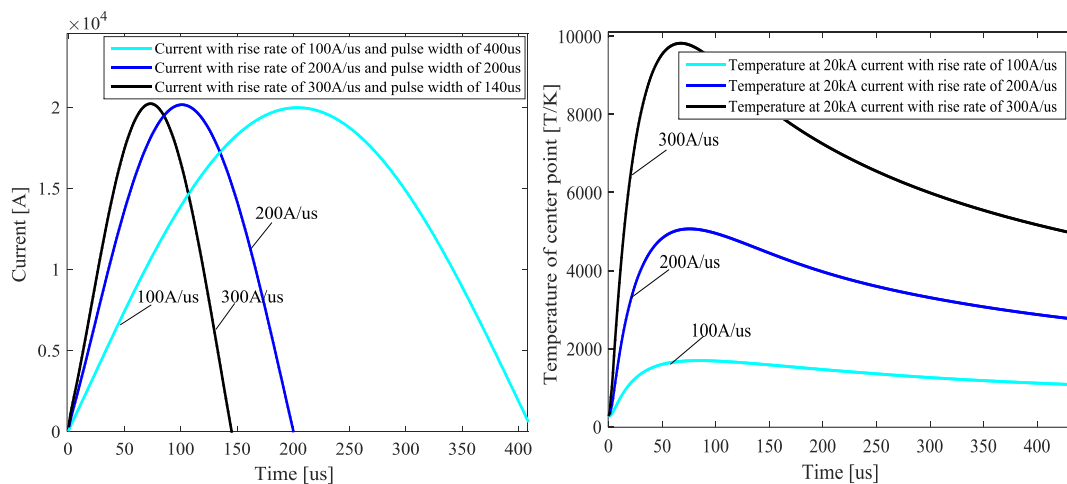


Fig.6 current waveform with different rise rate **Fig.7** Temperature at different rise rate

Figure 7 shows that the temperature rise of the thyristor of the average current rise rate of 100A/ μ s is the lowest, the corresponding maximum temperature peak is 1650K; the temperature rise of the thyristor of the average current rise rate of 200A/ μ s is the second, the corresponding maximum

temperature peak is 4900K; the temperature rise of the thyristor of the average current rise rate of 200A/ μ s is the highest, and the corresponding maximum temperature peak is 9820K. The simulation results show that the higher the external current rise rate, the higher the maximum temperature of the thyristor. The specific reasons are analyzed as follows.

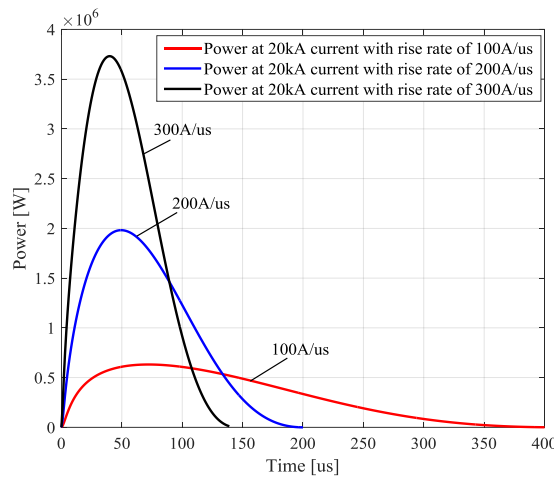


Fig.8 Power at different rise rate

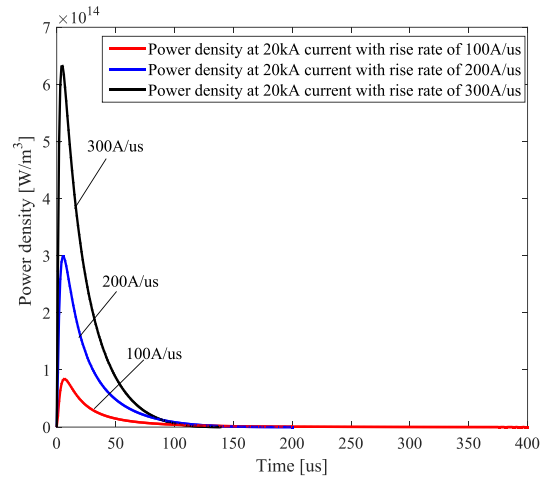


Fig.9 Power density at different rise rate

Figure 8 shows the power curve and Figure 9 shows the power density curve. Figure 8 and Figure 9 show that the greater the current rise rate, the greater the power and power density injected to thyristor. Taking the average current rise rate of 300A/ μ s to the peak current time of 70 μ s as an example, the current extends from the center gate to the cathode for 70 μ s at a constant speed of 100m/s, and the extension radius is 7mm. The slope resistance of the thyristor is also determined to be a certain value at 70 μ s. For a current with an average current rise rate of 100 A/ μ s, 200 A/ μ s, and 300 A/ μ s, the current at 70 μ s rises to amplitudes of 10 kA, 17 kA, and 20 kA, respectively. At 70 μ s, the extended area and slope resistance are fixed to a certain value, so the magnitude of the current is a direct and important factor affecting the magnitude of the injected power. The injected power density will increase the temperature rise in the thyristor conduction region, the higher the power density, the higher the temperature rise of the thyristor.

4.2. Effect of chip radius on temperature field distribution

In practical engineering applications, under the premise of meeting performance requirements, from the perspective of economical applicability and volume miniaturization, it is desirable that the volume of the thyristor is as small as possible. In this section, the influence of the radius of the thyristor on the transient temperature field distribution in the field of large inrush current are investigated. Five kinds of chip sizes, 5mm, 10mm, 20mm, 40mm and 60mm, are set for the single gate thyristor. The simulated current conditions are sinusoidal half-wave current with a rise rate of 200A/ μ s, a pulse width of 200 μ s, and a peak of 20kA. Assuming that the thyristor has a turn-on speed of 100m/s, the temperature distribution curve of the thyristor center point at different radii is obtained, as shown in Figure 11.

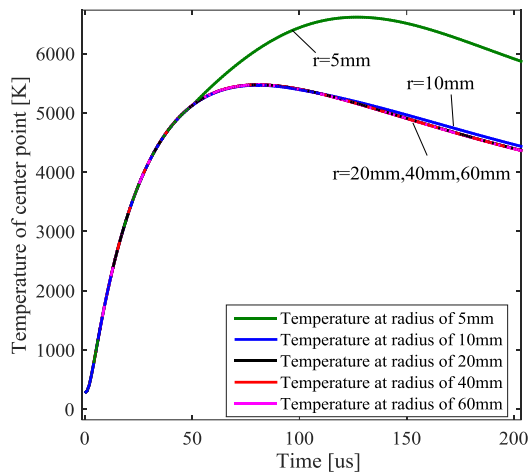
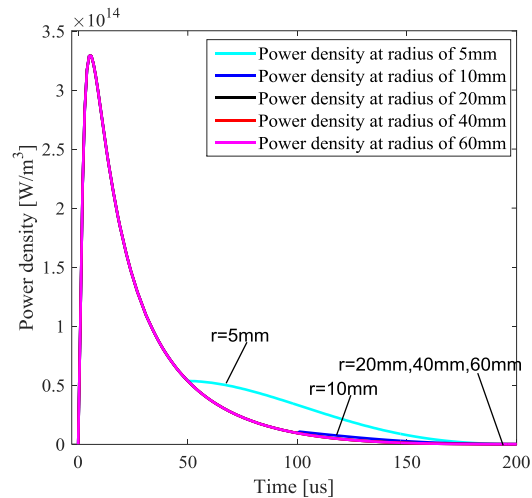
**Fig.10** Temperature at different radius**Fig.11** Power density at different radius

Figure 10 shows that at 0-50 μ s, the thyristors with a radius of 5mm and the thyristors with a radius of 10mm, 20mm, 40mm, 60mm have the same temperature curve and the temperature rise is consistent. At 50 μ s-200 μ s, the temperature of the thyristor with a radius of 5mm is more obvious than that of other radius thyristors, and the overall temperature rise is the highest. At 100 μ s-200 μ s, the temperature rise of the thyristor with a radius of 10mm is slightly higher than the radius of 20mm, 40mm and 60mm thyristors. During the entire flow process from 0 to 200 μ s, the temperature curves of the thyristors with a radius of 20 mm, 40 mm, and 60 mm coincide, and the temperature rise is consistent. The simulation results show that the temperature rise and the amplitude of the thyristors with different radii at the beginning coincide, but at a certain turning point, the temperature amplitude and trend change, which is related to the radius of the thyristor and the time when the current is fully expanded. The specific analysis is as follows.

It is assumed that different radii of thyristors have the same power when the injection currents are the same. Figure 10 shows the corresponding injected power density for thyristors of different radii. When the radius of the current expansion is smaller than the radius of the thyristor, the thyristors of different radii have the same conduction area, and the power density injected to the thyristor is the same. At 50 μ s, the radius of current expansion is 5mm. As the current continues to expand, for a thyristor with a radius of 5mm, the current does not have room to expand outward. Therefore, after 50 μ s, the power is loaded on the whole chip, the corresponding power density is larger than that of the thyristors with radii of 10mm, 20mm, 40mm, 60mm, and the temperature rise is larger. Similarly, the thyristor with a radius of 10 mm has a higher power density than that of a thyristor with radii of 20 mm, 40 mm, and 60 mm after 100 μ s, and the temperature rise amplitude increases. Since the radius of the current is completely expanded by 20 mm, the power density of the injection is the same for the thyristors with radii of 20 mm, 40 mm, and 60 mm throughout the whole process, so the temperature rise is the same.

In summary, the effect of chip radius on thyristor temperature is related to the pulse width of large inrush current. When the chip radius is smaller than the extended radius corresponding to the current pulse width, the smaller the radius, the higher the maximum temperature rise. When the radius of the chip is equal to or greater than the extended radius corresponding to the current pulse width, increasing the radius of the chip has no effect on the highest temperature rise.

5. Conclusion

In this paper, the thermal field model of thyristor turn-on process is established for the phenomenon of thyristor gate overheating damage under large inrush current. The transient temperature field

distribution of thyristor is obtained by simulation, providing a basis for the rational selection of thyristors. Main conclusions are as follows.

(1) Under large inrush current, the temperature distribution on the thyristor silicon chip is not uniform, and the temperature at the center gate is the highest, and the temperature gradually decreases from the center point to the radius direction.

(2) The high current rise rate is an important cause of damage to the center gate of the thyristor. The higher the current rise rate, the higher the temperature of the thyristor center gate

(3) When selecting the thyristor radius, it needs to be determined according to the current pulse width. When the chip radius is smaller than the extended radius corresponding to the current pulse width, the smaller the radius, the higher the maximum temperature rise. When the radius of the chip is equal to or greater than the extended radius corresponding to the current pulse width, increasing the radius of the chip has no effect on the highest temperature rise.

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