THERMAL STRESSES OF FUSES AND PROTECTED SEMICONDUCTOR DEVICES

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Abstract: The paper presents thermal stresses of fuses and semiconductor devices (particularly for a type of ultra-rapid fuse and protected semiconductor devices such as thyristor) for different current waveforms through ones.

The research of thermal stresses is doing through tantamount to RC circuits of thermal models of considered devices. Transient conditions' analysing to electrical circuits is doing with EMTP software.

I. INTRODUCTION

The rectifier semiconductor devices (diodes, thyristors) are very sensitive to overcurrents. The losses due to those overcurrents bring about overheating of junctions that can destroy the semiconductor device. The semiconductor devices can support overcurrents only a limited short time, that time depending on the overcurrent values. The thyristor limiting thermal characteristic is shown, in principle, in Fig. 1, curve no. 1. It indicates the time how long can be supported the overcurrent, depending on the ratio value between overcurrent (I_{oc}) and rated current (I_n). So, it is necessary a protection to interrupt the current before to reach the limit value.

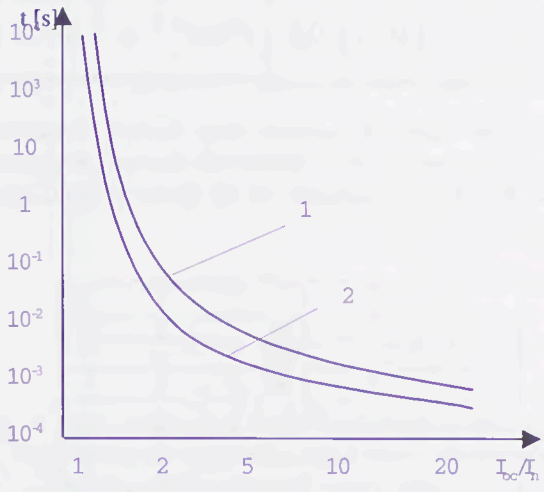

Fig. 1: The thyristor limiting thermal characteristic (curve no. 1) and time-current characteristic of fuse (curve no. 2).

One of the protection achievement means is by using ultra-rapid fuses. In this case it must be a full co-ordination between time-current characteristic (Fig. 1, curve no. 2) of fuse and limiting thermal characteristic of protected semiconductor device.

II. MODELING WITH RC CIRCUITS OF ELECTRIC FUSES AND SEMICONDUCTOR DEVICES

II.1. Analogy between thermal and electrical field

The thermal resistance between medium 1 and medium 2 could be written:

$$R_{t12} = \frac{\Delta\theta}{P}, \qquad (1)$$

where: $\Delta\theta=\theta_1-\theta_2$, over temperature between medium 1 and medium 2; P, the thermal flux.

The thermal resistance of conduction is determinate by similar relation with electrical resistance:

$$R_{t12} = \frac{d}{\lambda \cdot S}, \qquad R_e = \frac{\rho \cdot l}{S}, \qquad (2)$$

where: λ, thermal conductivity; ρ, electrical resistivity; d, l, length; S, section. For heat exchange with convection the thermal resistance is calculated with following relation:

$$R_c = \frac{\Delta\theta}{\alpha_c \cdot S_c}, \qquad (3)$$

where: α_C, the thermal transfer coefficient for convection; S_C, the exchange surface for convection.

The thermal capacity, respectively electrical is give by following expressions:

$$C_t = \frac{\int_0^t P \cdot dt}{\Delta\theta}, \qquad C_e = \frac{\int_0^t i \cdot dt}{u}. \qquad (4)$$

The analogy between thermal and electrical parameters is shown in Tab. 1, [1], [3].

Tab. 1

Thermal parameters	Electrical parameters
Flux - P [W]	Electrical current - I [A]
Density of thermal flux - q - linear [W/m] - surface [W/m^2]	Density of current - j - linear [A/m] - surface [A/m^2]
Temperature - θ [°C] Over-temperature - Δθ [°C]	Potential - V [V] Voltage - U [V]
Thermal resistance – R [°C/W]	Electrical resistance – R [ohm]
Thermal capacity – C [J/°C]	Electrical capacity – C [As/V]
Ohm law - P = Δθ/R	Ohm law - I = U/R

II.2. RC models for electric fuses and semiconductor devices

For modeling, it was considered the ultra-rapid fuses type UR by 40 A and thyristor T63N by 63 A, these devices being component parts of commanded rectifier type RUT.

The fuse constructive structure was divided in 3D cells like one from Fig. 2 [2], [4], [6].

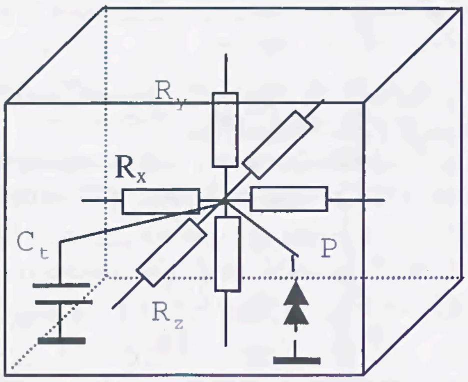

Fig. 2: Elementary cell of RC models for electric fuses.

The equivalent thermal resistances R_x, R_y and R_z which characterize each direction was divided (fifty-fifty) and are connected between central knot and each face. There are connected in the central knot of each cell the equivalent thermal capacity C_t together with current source P which means the thermal flux because of Joule losses. The current source P will be present only to the cells that contain component parts from conducting wire flowing by the electrical current (for instance, the fuse links).

In the case of semiconductor device assuming cylinder symmetry, the equivalent thermal circuit of semiconductor device contains concentrated thermal resistances and capacities Fig. 3. The meaning of notation are the following: $R_{J\text{-}C}$, $R_{C\text{-}R}$, $R_{R\text{-}A}$ the junction-case, case-heatsink, heatsink-environment thermal resistances; C_J, C_C, C_R, - the junction, case and heatsink thermal capacities; P_j thermal flux because of loss power into semiconductor.

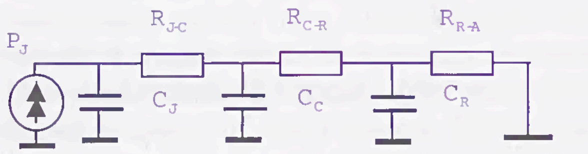

Fig. 3: The equivalent thermal circuit of semiconductor device with concentrated thermal resistances and capacities.

The forward mean power loss in a period of time can be calculate with the relation:

$$P_J = \frac{1}{T}\int_0^T u_F i_F dt = \frac{1}{T}\int_0^T (U_{T0} + r_T i_F) i_F dt =$$
$$= U_{T0} I_{Tmed} + r_T I_{Tef}^2, \qquad (5)$$

where: U_{TO} - threshold on-state voltage; r_T – equivalent resistance; I_{Tmed} – root mean square (r.m.s.) on-state current; T – period of time.

Referring to internal constructive structure of thyristor type T63N (the layers of silicium, molybdenum, copper), its case (B27) and considering an aluminium heat type TNF, it was calculated the values of thermal resistances and capacities, Tab. 2 [5].

Tab. 2

Thermal resistance [°C/W]			Thermal Capacities [J/°C]		
$R_{J\text{-}C}$	$R_{C\text{-}R}$	$R_{R\text{-}A}$	C_J	C_C	C_R
0,417 (a.c. 180 °el) 0,4 (d.c.)	0,08	0,6	4,5 10^{-3}	25	577,39

The value of junction-case thermal resistance $R_{J\text{-}C}$ is increasing with additional thermal resistance Δr(α), Fig. 4, [5], depending on the thyristor conduction angle α.

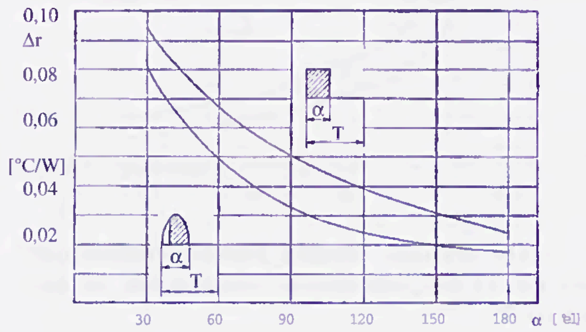

Fig. 4: The additional thermal resistance Δr(α) vs. thyristor conduction angle α.

III. NUMERICAL RESULTS

The study of thermal stresses is doing through equalization of thermal models of considered devices with RC electrical circuits, using the analogies from Tab. 1. The analysis of transient conditions from electrical circuits is doing with EMTP software.

For a mean on-state current by 63 A, the over temperature on junction Δθ is about 105.7 °C and on case is about 64.4 °C, Fig. 5.

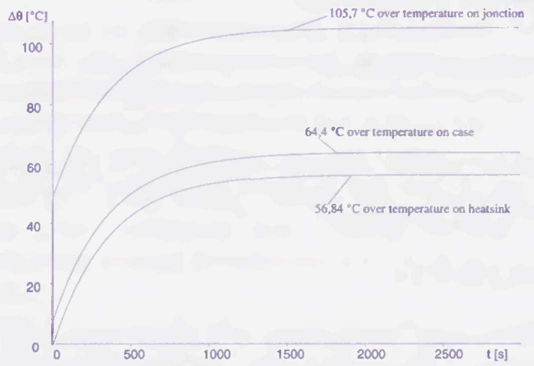

Fig. 5: The over temperatures in various points for a mean on-state current by 63 A.

To an environment temperature by 20 °C, these values are checking by sheet data: 125 °C – operating junction temperature; 85 °C – case temperature.

In Fig. 6 are shown the evolution of over temperature Δθ in the case of thyristor and fuse in the next condition: sinusoidal r.m.s. current by 40 A, conduction angle by 180 °el. and 120 °el.

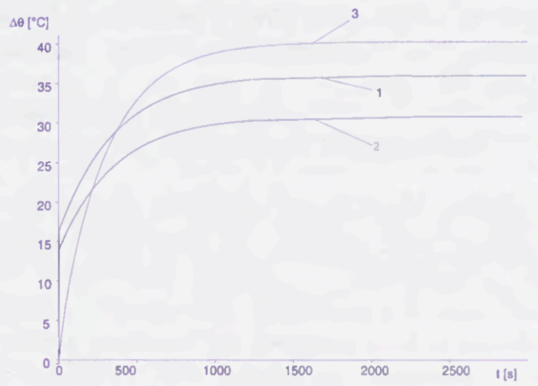

Fig. 6: The evolution of over temperature in the case of thyristor and fuse for a sinusoidal r.m.s. current by 40 A, conduction angle by 180 °el. and 120 °el.

It notes that over temperature on thyristor junction is about 35.91 °C (curve no. 1) for 180 °el conduction angle, respectively 30.8 °C (curve no. 2) for α=120 °el and 40.18 °C (curve no. 3) on fuse link.

The operating condition over temperature is the same in the case of fuse link because the loss power depends on r.m.s. current value, but in the case of junction, the loss power depends also on mean current value which is different in these two cases.

The evolutions of over temperature Δθ on fuse link and thyristor junction in the next conditions: square pulses r.m.s. current by 40 A, conduction angle by 180 °el and 120 °el, respectively direct current (d.c) are shown in Fig. 7.

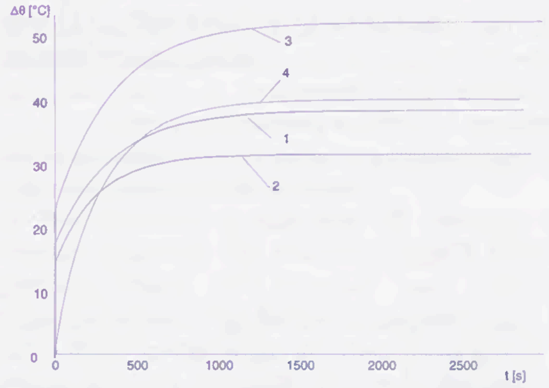

Fig. 7: The evolutions of over temperature on fuse link and thyristor junction for square pulses r.m.s. current by 40 A, conduction angle by 180 °el and 120 °el, respectively direct current (d.c).

The operating conditions over temperatures on junction are 39.4 °C (α=180 °el, curve no. 1) 31.9 °C (α=120 °el, curve no. 1), respectively 52.01 °C to d.c. (curve no. 3). The over temperature value on fuse link has the same value like in the previous case 40.18 °C (curve no. 4).

The evolution from Fig. 8 and Fig. 9 is getting for a sinusoidal overcurrent, respectively square pulse overcurrent with a period by 10 ms and r.m.s. current value by 282 A where is noted: 1 – junction over temperature; 2 – fuse link over temperature; 3 – thyristor junction loss power.

It notices that while on junction the maximum over temperature are approximately equal (223.8 °C – sinusoidal current, 219.3 °C – square pulse current), the over temperature on fuse link, in the same moment has higher values in the case of square pulse current. The over temperature in the case of square pulse current, because of small time thermal constant of junction (about 2 ms), is getting fast an approximately constant value. Further on, its rising is very little observable because the case time thermal constant is about seconds.

On these characteristics, the melting temperature of silver fuse link is reached in 6.3 ms to sinusoidal pulse current, respectively in 48 ms to square pulse current. So, it can affirm that in the case of square fault currents the fuse will work faster.

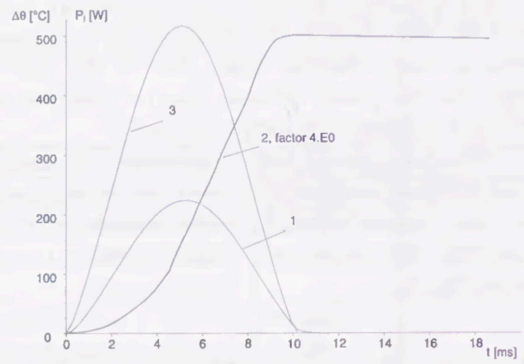

Fig. 8: The evolutions for a sinusoidal overcurrent with a period by 10 ms and r.m.s. current value by 282 A. 1 – junction over temperature; 2 – fuse link over temperature; 3 – thyristor junction loss power.

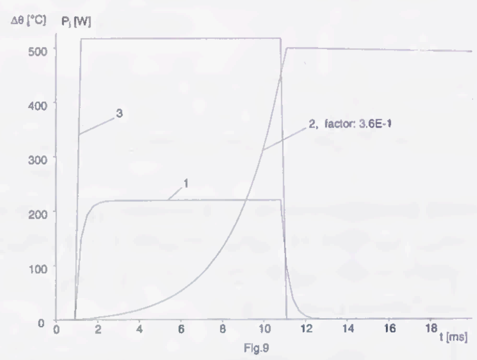

Fig. 9: The evolutions for a square pulse overcurrent with a period by 10 ms and r.m.s. current value by 282 A. 1 – junction over temperature; 2 – fuse link over temperature; 3 – thyristor junction loss power.

It comes out, experimentally, that at a sinusoidal pulse current with a period of 10 ms and r.m.s. current value by 1400 A, the thyristor destroyed after 273 ms from the moment when the electrical current was in the circuit. On the thermal model of thyristor, at this moment is reached the melting temperature of silicium (1412 °C). In the case of fuses, at this current is reached the melting temperature of silver (960 °C) after 0.54 ms. This fact shows that the fuse can protect the thyristor if the period of time between fuse melting time and electric arc extinguish doesn't exceed 2.19 ms.

IV. CONCLUSIONS

The EMTP software allows thermal stresses simulation of fuses and semiconductor devices using the analogy between electrical and thermal parameters.

The operating conditions over temperature for ordinary currents, the case of thyristor, are bigger for square pulses current then sinusoidal current, at the same r.m.s. current value.

The numerical results show that, in the case of short-circuit currents, the fuses prearcing time is smaller for square pulses current then sinusoidal pulses current.

The analyses and simulation of thermal processes using this method allow to establish easily the thermal stresses of fuses and thyristors at different evolution of current and overcurrents.

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