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ON THE SPREADING OF THE TURN-ON ACTION ACROSS THE AREA OF POWER THYRISTORS

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А. КРУУСИНГ. О РАСПРОСТРАНЕНИИ ВКЛЮЧЕННОГО СОСТОЯНИЯ ПО ПЛОЩАДИ СИЛОВЫХ ТИРИСТОРОВ

(Presented by I. Öpik)

It is known that power thyristors turn on first in a small region near the gate and then the turn-on action spreads with a finite velocity across the entire area of the semiconductor pellet of the device [1, 2]. During the spreading interval three qualitatively different regions can be distinguished: the on-region and the off-region where the values of the state quantities (that is current density, carrier densities, field, etc.) do not vary considerably over the area, and the transient region where these values are subjected to change within a short interval [2, 3]. The experiments revealed also that the configuration of these variables in the transient region does not depend significantly upon the current density, place and time.

This permits one to define the boundary of the turned-on region as a place where the value of any of the state quantities reaches a predetermined relative level (e. g. where the intensity of the recombination radiation drops up to the 50 per cent level of its value in the turned-on region [4, 5].

The spreading boundary defined this way represents a continuous smooth curve on the surface of the thyristor. In this paper we will propose a mathematical model describing this curve and, hence, the turn-on action as well.

The progress of the spreading boundary in time can be regarded as a determination of a certain «field of time» $t(x, y)$ on the surface of the thyristor. Next, let us define the local instantaneous spreading velocity as the velocity of a point on the spreading boundary in the direction of the normal. Then the definition of the spreading velocity within the limits of this model will be

$$\vec{v}=\frac{1}{|\operatorname{grad} t|}\frac{\operatorname{grad} t}{|\operatorname{grad} t|}.$$

For the moduli it will be valid as

$$v=1/|\operatorname{grad} t| \quad \text{or} \quad v^2=1/(\operatorname{grad} t)^2.$$

Assuming that the spreading velocity depends only on the space coordinates x, y (for the non-uniform structure of the thyristor) and on the current density j, but not on the spreading direction or the curvature of the boundary, we obtain from the given definition of the spreading velocity the differential equation for the boundary of the turned-on region

$$(\mathrm{grad}\, t)^2 = 1/v^2(x, y, j), \tag{1}$$

where now we regard $v(x, y, j)$ as known.

The equation (1) fully corresponds to the equation of the propagation of wave front for a short-wave electromagnetic radiation in a non-isotropic medium [6].

The experiments [4, 7–9] have shown that in the case of sufficiently high current densities the current distributes rather uniformly over the on-region, and spreading velocity does not depend explicitly upon the place and time, but rather upon the current density $v = v(j)$. In that case we can write (1) as follows

$$(\mathrm{grad}\, t)^2 = 1/v^2(j). \tag{2}$$

Equation (2) represents a spreading process where the form of the boundary, passing through a certain point, does not depend on the prehistory, but only on the initial conditions of the spreading, i. e. on the gate — cathode configuration of the thyristor.

This circumstance enables us to derive a simple general relationship between the voltage, current and turned-on area of a thyristor.

Thus let us consider the progress of spreading boundary during a short time interval Δt. If the spreading velocity is constant along all the free boundary of the on-region, then the increase of the current carrying area during Δt will be $\Delta s = l(s)\, v(j)\, \Delta t$, where s is the conductive area of the thyristor, and $l(s)$ is the length of the free boundary of the conductive area.

If $\Delta t \to 0$, this relationship becomes

$$\frac{ds}{dt} = l(s)\, v(j). \tag{3}$$

(This equation was first given in [8]).

In the case of uniform distribution of the current density in the on-region and at moderate dj/dt, the anode voltage of the thyristor unambiguously depends upon the current density in the turned-on region

$$u = u(j), \tag{4}$$

independently of the shape of the spreading boundary and time [4].

Further, considering $j = i/s$, where i is the anode current of the thyristor, we get from (3) and (4)

$$u = u(i/s), \tag{5}$$

$$\frac{ds}{dt} = l(s)\, v(i/s). \tag{6}$$

The equations (5) and (6) determine the state of the thyristor (i. e. the values of i, u, and s) during the plasma spreading interval for an arbitrary thyristor connected into an arbitrary circuit (as long as $u(j)$ and $v(j)$ are invariant in place and time).

The function $l(s)$ can be found by the equation (2) or the simplified form of it $(\operatorname{grad} t)^2=\text{const}$.

The functions $u(j)$ and $v(j)$ can be determined by the microscopic theory of plasma spreading, or experimentally.

For the determination of $u(j)$ the processes $i(t)$, $u(t)$ and $s(t)$ must be recorded. Thereupon $j(t)=i(t)/s(t)$ will be found and t will be eliminated from $u(t)$ and $j(t)$.

In order to find $v(j)$, the path length $w(t)$ of a point on the spreading boundary along the trajectory orthogonal to the boundary, must be recorded and subsequently $v(t)=dw(t)/dt$ must be calculated. Then t will be eliminated from $v(t)$ and $j(t)$.

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