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OPTIMAL TURN-ON OF THYRISTORS

(Presented by I. Öpik)

The turn-on losses in power thyristors related to plasma spreading, have been a serious problem until large area power devices were introduced [1–3] and have been the subject for a great amount of investigations and developments. In order to reduce the turn-on losses, the field-initiated, regenerative, amplifying and distributed gates were introduced. A number of theories on plasma spreading have been created to find out how the device design parameters affect the spreading process. Much investigation work has been carried out to enable accurate measurements of plasma spreading parameters, to prove the theory and to provide the data for correct calculations of thyristor ratings in dynamical modes of operation [4–7].

Besides, relatively restricted attention has been paid to a different way of affecting the turn-on losses. It has long been known that the switching losses can be effectively reduced by the use of saturable reactors in series with thyristors [2, 8–11]. The reactor holds the load current on a relatively low level during the initial phase of turn-on, limiting so the current density and hence the power dissipation. When the core saturates, the conductive area has already increased and the current inrush does not cause such high losses as without it.

This experience indicates that it is possible to reduce the switching losses by controlling the load current of the device. Probably certain current waveform exists with the turn-on losses having a minimal value. In this paper we shall try to find such a waveform. (In [12] a related problem was analyzed, not for seeking the optimal switching process, but for calculating the inner dynamic variables of the device (turned-on area and spreading velocity) from measured current and voltage waveforms employing the minimum dissipated energy principle.)

To solve the problem theoretically, the preliminary condition is to have a dynamical model of the thyristor which holds for any current waveform. In [13] such a model, in a rather general form, was proposed

$$u=u(i/s), \tag{1}$$

$$s'=l(s)\,v(i/s), \tag{2}$$

where u denotes the voltage and i the current of the device, s is the turned-on area, v the plasma spreading velocity and l the length of the free turn-on area boundary line. The model considers the plasma spread as a solely lateral process and it holds, beginning from 5—10 μs after the device is fired. Here we extend somewhat arbitrarily the validity of the model till $t=0$, neglecting the initial turn-on effects [14, 15] and set $s(0)=0$. Similar approach was used in [6, 12, 16, 17] and elsewhere.

Now let us consider the optimization problem itself. First we shall examine the case of minimization of not total, but specific turn-on losses, occurring in the unit conductive area of the device.

$$E_j = \int_0^T s^{-1} iu\, dt = \min. \quad (3)$$

As we shall see below, this problem is less complicated than the first one. If the thyristor is operating in pulse mode, E_j will be even a more significant parameter than the total turn-on losses, because it determines the hot-spot peak temperature.

Since we have not imposed any restrictions upon the variables in (1), (2), it is most convenient to apply the calculus of variations here. For that we have first to represent the problem in some modified form, the integrand must be the function of (s', s, t).

From (2) we get

$$i/s = \bar{v}[s'/l(s)], \quad (4)$$

where $\bar{v}$ denotes the inverse function of v. Inserting the equations (1) and (4) into (3), we obtain

$$E_j = \int_0^T \bar{v}[s'/l(s)]\, u\{\bar{v}[s'/l(s)]\}\, dt = \min, \quad (5)$$

or

$$E_j = \int_0^T w[s'/l(s)]\, dt = \min, \quad (6)$$

where the function w is defined as

$$w(x) = \bar{v}(x)\, u[\bar{v}(x)]. \quad (7)$$

The equation (6) represents the Lagrange problem in the calculus of variations and can be solved by the Euler-Lagrange method [18].

For (6) the Euler-Lagrange equation is

$$[s'/l(s)]\, w'[s'/l(s)] - w[s'/l(s)] = \text{const}. \quad (8)$$

The equality will be valid, if

$$s'/l(s) = \text{const}. \quad (9)$$

Substituting (9) into (4), we get the following condition for optimum:

$$i/s = \text{const}. \quad (10)$$

Hence, the minimum specific turn-on losses occur if the thyristor is turned on at the constant current density in the conductive area. The corresponding current waveform may easily be found from the equation (2). Its shape is obviously determined by the thyristor geometry only.

To illustrate the obtained result, the optimal current waveforms and corresponding switching losses for three model thyristors, specified in Fig. 1, were calculated (Fig. 2, Table). All the thyristors had the same active area $S_M = 2{,}47\pi$ cm² and the spreading pathlength $d = 1.3$ cm. The functions v and u were given by

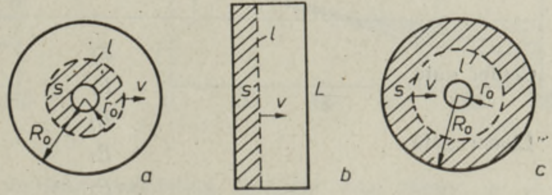


Fig. 1. Model thyristors used for calculations: *a* — centrally symmetrical with center gate, $r_0 = 0.3$ cm, $R_0 = 1.6$ cm, $l(s) = 2\sqrt{\pi(\pi r_0^2 + s)}$; *b* — rectangular with linear gate, $d = 1.3$ cm, $l = L = 1.9\pi$ cm; *c* — centrally symmetrical with perimeter gate, $r_0 = 0.3$ cm, $R_0 = 1.6$ cm, $l(s) = 2\sqrt{\pi(\pi R_0^2 - s)}$.

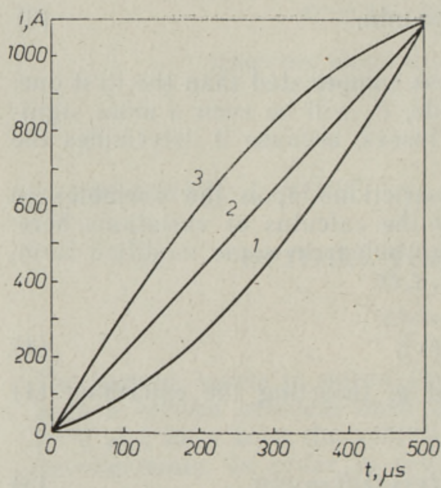


Fig. 2. Current waveforms optimizing specific turn-on losses: *1* — center gate thyristor, $i=\pi Jv(J)[2r_0/v(J)+t]t$; *2* — linear gate thyristor, $i=LJv(J)t$; *3* — perimeter gate thyristor, $i=\pi Jv(J)\times$ $\times[2R_0/v(J)-t]t$.

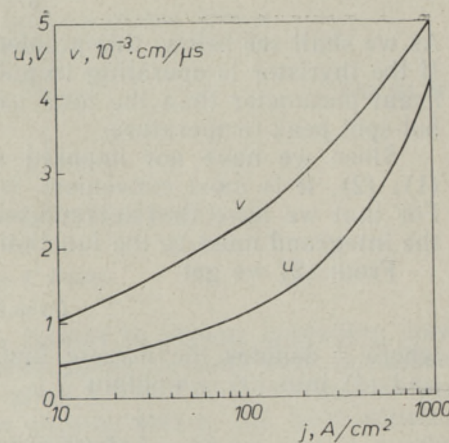


Fig. 3. Forward voltage drop and plasma spreading velocity versus current density characteristics used in calculations.

$$v(j)=0.0005\sqrt[3]{j},$$

and

$$u(j)=0.18\ln(j+1)+0.003j \qquad (11)$$

(j in A/cm², u in V, v in cm/μs, see also Fig. 3), as a typical embodiment of a contemporary high power thyristor [17]. The value of the current density J was determined from the condition that at the end of the chosen time interval $T=500$ μs the whole device was turned on.

Let us consider now the problem of minimizing the total turn-on losses in a thyristor

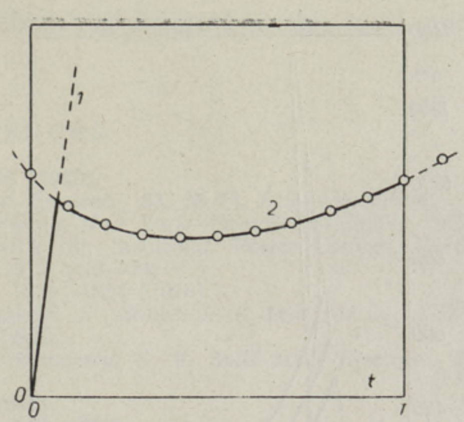
$$E_i=\int_0^T iu\,dt=\min. \qquad (12)$$

If we are going to use the calculus of variations in this case, we shall come across several difficulties. First, it will become apparent that we cannot proceed without imposing restrictions on $i(t)$. If we let $i(t)$ free,

Calculated turn-on losses (J and J/cm² per transient)

Thyristor modification	Type of losses	Turn-on mode		
		Linear current rise	Minimal specific losses	Minimal total losses
Center gate	E_j	0.117	0.092	0.154
	E_i	0.231	0.277	0.202
Linear gate	E_j	0.092	0.092	0.135
	E_i	0.358	0.358	0.295
Perimeter gate	E_j	0.108	0.092	0.128
	E_i	0.445	0.440	0.379

Fig. 4. Simulation of current waveforms for the minimization of total losses: *1* — j=constant-curve, *2* — spline-function.



the initial current density $j(0)$ will tend to infinity. Second, the analytical solution will have, despite the simplicity of the problem, a rather complicated form, including several inverse functions and derivatives that will significantly harm its practical computation.

More convenient, in our opinion will be a direct optimization procedure. Here we shall simply vary the current waveform and compare the successive values of E_i until we reach its minimum. To reduce the dimensionality of the vector $i(t)$, we specified the current at 12 evenly dis-

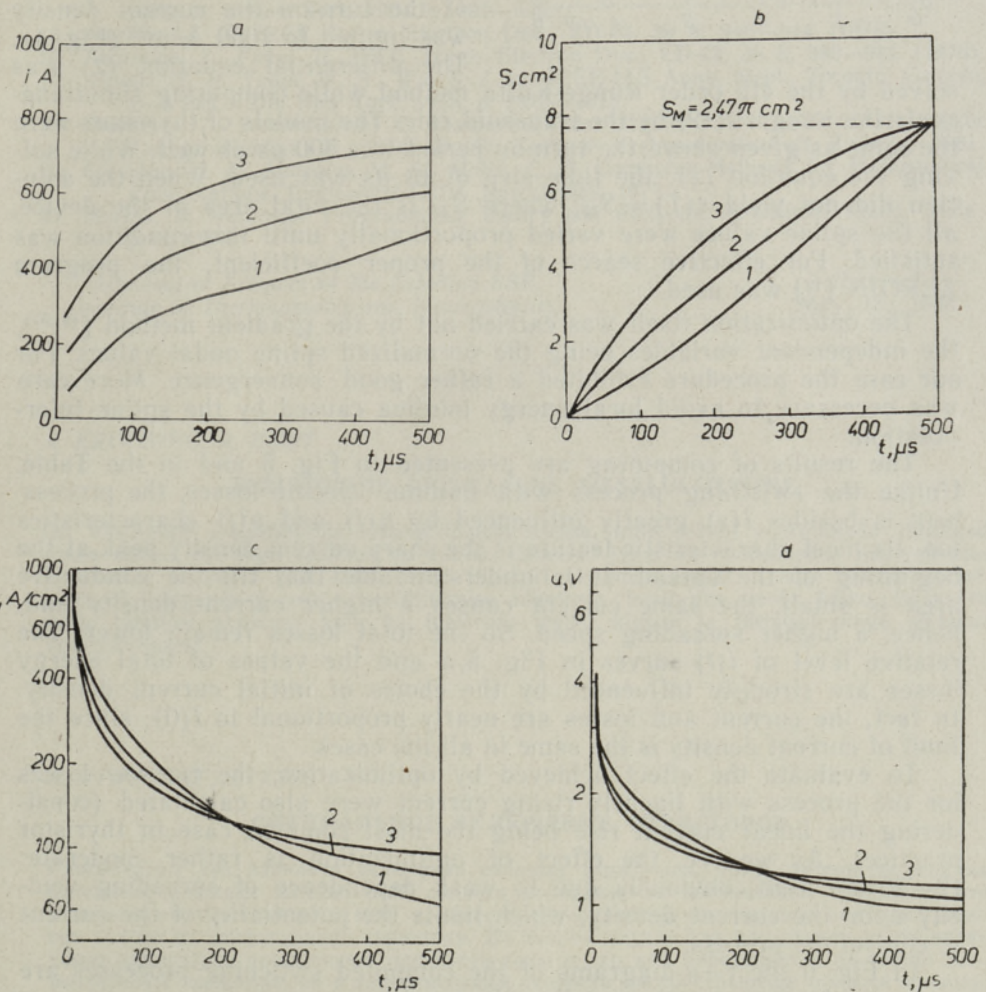


Fig. 5. Turn-on processes of model thyristors exhibiting minimal total losses: *a* — current, *b* — current carrying area, *c* — current density, *d* — voltage drop. *1* — center gate thyristor, *2* — linear gate thyristor, *3* — perimeter gate thyristor.

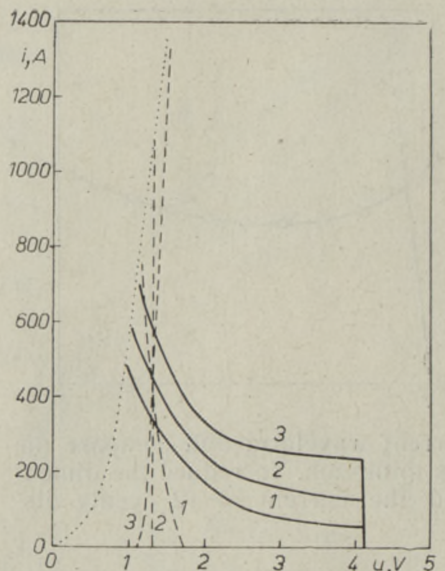


Fig. 6. *i—u*-diagrams of switching processes in model thyristors. Solid lines — optimal processes with regard to total losses, dash lines — processes with linear current rise, dotted line — static *i—u*-characteristic. *1* — center gate thyristor, *2* — linear gate thyristor, *3* — perimeter gate thyristor. The dash line *2* represents also the processes with minimal specific losses for all three modifications of model thyristors.

tributed time moments and used the cubic spline for getting the rest of the values. The construction of the spline and the computation of its values were accomplished by the programs SPLINE and SEVAL, presented in [19]. At the initial stage of the turn-on the current density was limited to 1000 A/cm² (Fig. 4). The differential equation (2) was solved by the 4th order Runge-Kutta method, while computing simultaneously the integral (12) by the trapezoid rule. The models of thyristors were the same as given above, the turn-on period was 500 μs as well. While solving the equation (2), the time step of 10 μs was used. When the solution did not yield $s(T)=S_M$, where S_M is the total area of the device, all the spline values were varied proportionally until this condition was satisfied. For effective search of the proper coefficient, the program ZEROIN [19] was used.

The optimization itself was carried out by the gradient method [19, 20], the independent variables being the normalized spline nodal values. For our case the procedure exhibited a rather good convergence. More care was necessary to avoid local energy minima caused by the spline interpolation.

The results of computing are presented in Fig. 5 and in the Table. Unlike the switching process with minima specific losses, the process here is besides $l(s)$ greatly influenced by $u(j)$ and $v(j)$ characteristics too. Its most characteristic feature is the sharp current density peak at the beginning of the spread. It is understandable that till the conductive area is small, the same current causes a higher current density and, hence, a higher spreading speed. So the total losses remain lower. The relative level of $i(t)$-curves in Fig. 5, *a* and the values of total energy losses are strongly influenced by the choice of initial current density. In fact, the current and losses are nearly proportional to $l(0)$, since the limit of current density is the same in all the cases.

To evaluate the effect achieved by optimization, the turn-on losses for the process with linearly rising current were also calculated (considering the linear current rise being the most common case in thyristor practice). As we see, the effect of optimization is rather moderate: 12—20 per cent, obviously due to weak dependence of spreading velocity upon the current density, which limits the potentiality of the current to control the process.

In Fig. 6 the *i—u*-diagrams of the computed switching processes are presented for better understanding the results.

The optimization technique, presented here, may be used to develope optimal thyristor circuits. It may be reasonable to insert the temperature calculation into the optimization procedure.

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TÜRISTORIDE OPTIMAALNE SISSELÜLITUMINE

On käsitletud jõutüristoride sisselülitumisprotsesse, mille vältel energiakadu lülitunud pinna ühikul või kogu seadises on vähim. Esimesel juhul on voolutihedus juhtivas alas konstantne ja voolu käik sõltub vaid türistori aktiivosa kujust. Teisele juhule on iseloomulik kõrgenenud vool sisselülitumise algetapil, kusjuures voolu käiku määravad peale türistori aktiivosa kuju ka juhtivuse leviku kiiruse ja türistori pinge sõltuvus voolutihedusest.

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ОПТИМАЛЬНОЕ ВКЛЮЧЕНИЕ ТИРИСТОРОВ

Рассмотрены два варианта включения силовых тиристоров, когда потери энергии на единичной площади или во всей области проводимости минимальны. Показано, что в первом случае плотность тока в области проводимости постоянна и ход тока зависит только от конфигурации тиристора. Во втором случае для начального этапа включения характерна повышенная плотность тока, а его ход определяется не только конфигурацией тиристора, но и зависимостями скорости распространения области проводимости и падения напряжения от плотности тока.