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MODELING OF FREQUENCY RESPONCE CURVES OF POWER SEMICONDUCTOR DEVICES

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Physical principles of losses calculation and of average power losses calculation in power semiconductor diodes and thyristors are stated. The mathematical model, permitting to plot the frequency dependences of the sine current pulses amplitude at stationary conditions of devices is designed. By the example of devices DL343-630-34 and MT3-500 the comparative analysis of the diode and the thyristor frequency characteristics (the frequency response curves) is carried out.

1 Introduction

Frequency response curves fall into the most important characteristics of power semiconductors devices (PSC), since dynamic properties of devices, their output capacity and conditions of cooling, which indispensable for their normal operation depend largely on them.

Frequency response curves are usually interpreted as dependences of PSC different parameters on frequency and duration of current pulses and/or voltage, affecting them, which prescribed by the operational standards and expressed by way of diagrams, mathematical formulas, tables or numeric parameters. In the present paper basic physics of calculation of losses and average power losses in power thyristors and diodes at passing of sine current pulses through them are stated, and the mathematical model permitting to plot amplitude frequency dependences of these pulses at stationary conditions of devices' activity is designed.

The part of energy, which is released in PSC structures in the form of heat is called losses. At stationary conditions of a device activity this heat should be equal to energy retracted from this device at cooling. Therefore an average power loss for the period between pulses is

$$P(f,\tau) = \frac{T_j - T_c}{R_{th}}, \tag{1}$$

where f - pulses repetition rate, τ - their duration, T_j - steady-state temperature value of semiconductor structure, T_c- temperature of PSC package (cooler temperature), R_{th}- steady-state heat resistance value of «PSC structure - package» system.

The heat balance equation (1) underlies the mathematical model, formulated in the present paper.

2 Losses and average power of losses in power semiconducting thyristors

As it well known (see, for example, [1-3]), energy losses by activity of thyristors are composed of switching losses at turning the power on and off and losses at their activity in open condition. Thus,

$$P(f,\tau) = P_{TT}(f,\tau) + P_{AV}(f,\tau) + P_{RQ}(f,\tau), \quad (2)$$

where$P_{TT}(f,\tau)$ and $P_{RQ}(f,\tau)$ - average powers of switching losses at turning power on and off accordingly, $P_{AV}(f,\tau)$ - average power of losses by activity of a thyristor in open condition.

2.1 Switching losses at a thyristor actuation

A thyristor turning on implies the process of device transference from off (non conducting) state of low conductivity in on (conducting) state of high conductivity when applying a forward voltage to it. Thyristors *p-n-p-n*-structure actuation may be put into effect in different ways: by increase of voltage higher than some threshold value, by injection of a control current pulse in a base layer, by lighting of structure, by its heating etc. However a physical nature of all these methods lies in [1-3], that, some of majority carriers are injected at least, in one of the base layers of a thyristor, which stimulate minority carriers injection by emitter junction. Some part of injected carriers recombines in PSC base, and some part reaches collector junction and by the field of a bulk (space) charge layer is carried out in other base, where they serve as majority carriers.

In the base, these carriers cause an injection of minority carriers from the second emitter junction. For their turn, a part of emitter junction carriers recombines, and another part reaches collector junction and comes in the first base, which results in favourable conditions for increase of injection through the first emitter junction.

As a result the current flowing through the structure rises, the density of extra carriers in bases increases, and at getting of some value conforming to a critical charge of actuation, it starts to satisfy the conditions for the spontaneous regenerative current rise. From this moment to maintain the process of current rise there is no need to inject additionaly extra charge carriers in base layers: they enter there in sufficient quantity through a collector junction in consequence of current flowing through the device.

From the practical point of view the most commonly used and, therefore, the most interesting method is to actuate p-n-p-n-structure by a control current pulse. Therefore in the present article we shall limit ourself to consider in particular this method of a thyristor actuation.

Actuation of a thyristor by a control current pulse initially takes place in an area with the maximum control current density adjoining to a control gate [1-3]. Simultaneously this actuated state with the terminal velocity $v_0 \approx 10$ sm/ms [3] is transmitted throughout all the area of emitter junction. Such a nature of the real process of semiconductor structure actuation allows us to simplify its theoretical consideration and to conclude, that it consists of two independent processes: a unidimensional process of actuation covering events which occur along the current line, and a non unidimensional process of actuated state transmitting throughout the cathode area. Thus, an average power of switching losses

$$P_{TT}(f,\tau) = f \int_0^{t_{in}} i(t)\, u(t)\, \frac{S_K}{S(t)}\, dt\,, \tag{3}$$

where t_{in} - total time of a thyristor actuation; $i(t)$ - anode current flowing through a thyristor at its actuation; $u(t)$ - anod voltage conforming to this current; S_K - the maximum area of the cathode of a thyristor, which functions in an actuated state; $S(t)$ - area of cathode region, which is in an actuated state in instant of time t.

The difficulty of calculation of average power of switching losses (3) at actuation of a thyristor consists of that in the general case time evolution of anode current $i(t)$ and voltage $u(t)$ are rather complicated and depends on both the thyristor parameters, and the mode of its switching on to the open state (the source voltage, the loading nature of a power circuit, the amplitude and the rate of rise of a control current pulse etc.). The typical dependences of an anode current time and voltage, observed in practice at actuation of a thyristor, are shown in a fig. 1.

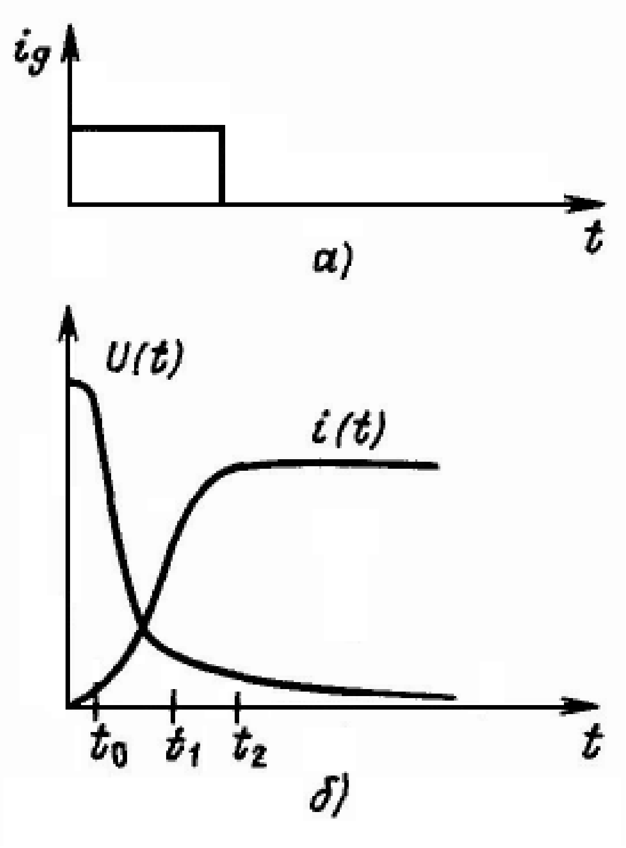

Fig. 1. Diagrams of control current i_g (*a*) time dependence and typical dependences of anode current $i(t)$ and voltage $u(t)$ *(б)* at a thyristor actuation by this control current.

As this figure shows, a thyristor actuation transient consists of three main points [1-4]: the delay, the current rise (voltage drop) and the stationary state.

The delay implies an initial stage of a thyristor actuation process from the moment of control current pulse (fig. 1, *a*) injection up to the moment t_0, corresponding to the beginning of anode current rise and anode voltage drop. At this stage the device voltage practically is not varied, and the thyristor leakage current rises slowly up to the switching current (fig. 1, *б*). Therefore at moderate temperatures T_j of semiconductor structure the loss of energy at a stage of delay appears insignificant, and at calculus of an average power of switching losses (3) we may ignore them:

$$P_{TT}(f,\tau) \approx f \int_{t_0}^{t_{in}} i(t)\, u(t)\, \frac{S_K}{S(t)}\, dt\,. \qquad (4)$$

The area of cathode region, which is in an actuated state, at the stage of delay also practically does not vary and is equal to the area S_0 of initial region of actuation of a thyristor (near the control gate), width of which is usually 0,3 - 0,6 mms [3].
Thus,

$$S(t) \approx \begin{cases} S_0 \text{ при } t \le t_0, \\ \pi\left(\sqrt{\dfrac{S_0}{\pi}} + v_0(t-t_0)\right)^2 \text{ при } t_0 < t < t_K, \\ S_K \text{ при } t \ge t_K, \end{cases} \qquad (5)$$

where t_K- time necessary for transmitting of actuated state all over the area of a cathode S_K:

$$t_K \approx t_0 + \frac{\sqrt{S_K} - \sqrt{S_0}}{v_0\sqrt{\pi}}\,. \qquad (6)$$

The time of delay t_0 includes the time t_d of charge carriers transit through base layers of semiconductor structure of a thyristor and time t_q of critical charge accumulation in these layers. It is necessary for transition of a thyristor in a conducting state:

$$t_0 = t_d + t_q\,. \qquad (7)$$

The time of transit t_d is conditioned only by design factors of the device and equals [4]:

$$t_d \approx 0{,}2\sqrt{\frac{W_n^2}{2D_p}\,\frac{W_p^2}{2D_n}}\,, \qquad (8)$$

where W_n and W_p - thickness of *n*-base and *p*-base of a thyristor accordingly, and D_n and D_p- diffusion constants of minority carriers in *n*-base and *p*-base accordingly, .
Making use of the Einstein relation, diffusion constants D_p and D_n may be expressed through mobilities μ_p and μ_n of charge carriers:

$$D_{n,p} \approx \frac{kT_j}{e}\, \mu_{n,p}\,, \qquad (9)$$

where *k* - Boltzmann constant, *e* - electron charge.

For their part mobilities μ_p and μ_n may be calculated, making use advantage of a sem-iempirical relation [5, 6]:

$$\mu_{n,p} \approx \mu_{0n,p}\left(\frac{300}{T_j}\right)^{5/2}, \tag{10}$$

where $\mu_{0n} \approx 1350$ sm^2/(B·c), and $\mu_{0p} \approx 480$ sm^2/(B·c) [6].
Considering equations (9) and (10), for time of transit (8) we receive:

$$t_d \approx 0{,}1\frac{eW_nW_p}{kT_j\sqrt{\mu_{0n}\mu_{0p}}}\left(\frac{T_j}{300}\right)^{5/2}. \tag{11}$$

Calculations made by the formula (11), show, that for production-run thyristors the time of transit t_d lies in the range from 3 up to 10 mcs.
The time of accumulation of critical charge t_q depends on the amplitude I_G of a control current pulse, and also from the strength of capacitive current I_{GC}, connected with the rise of anode voltage in off condition. In accord with [1], this time may be represented in the following way:

$$t_q \approx t_{gi}\ln\left(\frac{I_G + I_{GC}}{I_G + I_{GC} - I_{GT}(U_{TM})}\right), \tag{12}$$

where t_{gi} - time constants of the current build-up in the range from t_0 to t_1 (fig. 1, *б*), and $I_{GT}(U_{TM})$ - the minimum control current required for a thyristor actuation at a preset value U_{TM} of anode voltage.

The current I_{GC} is conditioned by availability of a barrier capacitance C on collector junction of a thyristor, which is generally speaking, depends on the applied anode voltage $U(t)$:

$$I_{GC} = \frac{d(CU)}{dt}. \tag{13}$$

The initiating of this current results in reduction of voltage of a thyristor switching in a conducting state with the increase of rate of anode voltage rise (effect dU/dt [1]).
Considering, that forward current sine pulses through a thyristor are conditioned by sinusoidal anode voltage

$$U(t) = U_{TM}\sin\left(\frac{\pi t}{\tau}\right), \tag{14}$$

where U_{TM} - peak voltage, and neglecting barrier capacitance C dependence on voltage, from (13) we come to:

$$I_{GC} \approx \frac{\pi C U_{TM}}{\tau}. \tag{15}$$

Thus, the capacitance C may be computed starting from the condition equality of control current $I_{GT}(U_{TM})$ and capacitive current (13), conforming to such a rate of anode voltage $(dU/dt)_{\max}$, when a thyristor is actuated spontaneously, without a control current pulse injection to a control gate:

$$C \approx \frac{I_{GT}(U_{TM})}{(dU/dt)_{\max}}. \tag{16}$$

The value $(dU/dt)_{\max}$ characterizes dU/dt-stability of a thyristor. As a rule, this value is determined experimentally and ranks among the most important parameters featuring dynamic properties of the device.

Subject to equations (15) and (16) the time of critical charge accumulation (12) may be represented in the following way:

$$t_q \approx t_{gi} \ln\left(\frac{I_G + \dfrac{\pi U_{TM}}{\tau (dU/dt)_{\max}} I_{GT}(U_{TM})}{I_G + \left[\dfrac{\pi U_{TM}}{\tau (dU/dt)_{\max}} - 1 \right] I_{GT}(U_{TM})} \right). \tag{17}$$

In that way, taking into consideration (11) and (17), for the delay time (7) we have:

$$t_0 = 0{,}1 \frac{eW_nW_p}{kT_j\sqrt{\mu_{0n}\mu_{0p}}} \left(\frac{T_j}{300} \right)^{5/2} + t_{gi} \ln\left(\frac{I_G + \dfrac{\pi U_{TM}}{\tau (dU/dt)_{\max}} I_{GT}(U_{TM})}{I_G + \left[\dfrac{\pi U_{TM}}{\tau (dU/dt)_{\max}} - 1 \right] I_{GT}(U_{TM})} \right). \tag{18}$$

At considerable amplitudes of control current pulses and steep edge of anode voltage the time of accumulation t_q tends to zero, and delay time t_0 - to its minimum value determined by transit time t_d [augend in expression (18)]. Along with the voltage rise applied to a thyristor in the forward direction, effective thicknesses of their base layers decrease owing to an expansion space charge layer of collector junction, that decreases the transit time t_d and also reduces time of delay of a thyristor actuation.

The delay stage duration(18) conditions minimum required duration of turn-on control current of a thyristor.

The dependence of anode current of a thyristor on the time at a stage of its rise (fig. 1 *б,* a perod t_0 - t_1) usually has the exponential nature [1-4]. Disregarding the change of current intensity at a stage of delay, this dependence may be presented as:

$$i(t) = I_s \exp\left(\frac{t - t_0}{t_{gi}} \right), \tag{19}$$

where I_s- leakage current conforming to an off-state of a thyristor [7].

Simultaneously with the anode current rise the anode voltage starts to decrease (fig. 1, *б*). At actuation of a thyristor for a resistive load, taking into consideration (14), the voltage dependence on the time may be described by the expression:

$$u(t) = U_{TM} \sin\left(\frac{\pi t_0}{\tau} \right) \exp\left(-\frac{t - t_0}{t_{gi}} \right). \tag{20}$$

The constant of the current rise t_{gi}, time, which is the part of formulas (19), (20) and (12), is determined by minority carriers generation rate via the first emitter junction. Specific values t_{gi}, which lie in the range from 0,3 up to 10 mcs [1] for production-run thyristors, are usually determined from the diagram of experimental dependence of anode current on the time, constructed in the semilogarithmic scale.

When decreasing anode voltage, becomes equal to n-base voltage drop, the stage of avalanche-like increase of anode current comes to its end. From this moment the stage of stationary state of a thyristor activity in an on-state starts (fig. 1,*б* ; a period t_1 - t_2).

This stage is accompanied by the increase of level of n-base conductivity modulation, thus the voltage drop on a thyristor proceeds to decrease and in the stationary state approaches the stationary value, lying in the range from some tenths of a volt up to some volts.

In non stationary state, for example, under conditions of constant voltage rise of an external source (14), the stage of steady state setting appears blurred. Therefore we may consider, that the dependences of anode current and voltage on the time look like (19) and (20) up to that moment t_2, when the rising anode current becomes equal to the forward current of a sine pulse, which would run through a thyristor opened in full:

$$i(t) \approx \begin{cases} I_s \exp\left(\dfrac{t-t_0}{t_{gi}}\right) \text{ при } t_0 \le t \le t_2, \\ I_{TM} \sin\left(\dfrac{\pi t}{\tau}\right) \text{ при } t \ge t_2, \end{cases} \tag{21}$$

where I_{TM} - amplitude of forward current pulses;

$$u(t) \approx \begin{cases} U_{TM} \sin\left(\dfrac{\pi t_0}{\tau}\right) \exp\left(-\dfrac{t-t_0}{t_{gi}}\right) \text{ при } t_0 \le t \le t_2, \\ U_0 + \dfrac{S_K}{S(t)} r\, i(t) \text{ при } t \ge t_2, \end{cases} \tag{22}$$

where U_0 - pinch-off voltage of linearized E-I curve of PSC device [7], r - dynamic resistance of the device in a conducting state.

In the last expression that fact, that the time of completion of one-dimensional process of actuation t_2 may be both more, and less than the time t_K of a thyristor actuation all over the cathode area, is taken into account. Thus the total time of a thyristor actuation is:

$$t_{in} = \begin{cases} t_2 \text{ при } t_2 \ge t_K, \\ t_K \text{ при } t_2 < t_K. \end{cases} \tag{23}$$

As it follows from the formula (21), the time t_2 is determined by the solution of the following equation:

$$I_s \exp\left(\frac{t_2 - t_0}{t_{gi}}\right) = I_{TM} \sin\left(\frac{\pi t_2}{\tau}\right). \tag{24}$$

The root of this equation is:

$$t_2 \approx t_0 + t_{gi} \ln\left(\frac{I_{TM}}{I_s}\right). \tag{25}$$

Expressions (4) - (6) together with equations (18), (21) - (23) and (25) completely determine an average power of switching losses conforming to processes of a thyristor actuation. If we integrate (4), we derive:

1) at $t_2 > t_K$

$$P_{TT}(f,\tau) \approx f I_s U_{TM} \sin\left(\frac{\pi t_0}{\tau}\right)\left[(t_{K1} - t_{K0})\frac{t_{K1}}{t_{K0}} + (t_2 - t_K)\right], \tag{26}$$

where

$$t_{K0} \equiv \frac{1}{v_0}\sqrt{\frac{S_0}{\pi}}\,, \tag{27}$$

$$t_{K1} \equiv \frac{1}{v_0}\sqrt{\frac{S_K}{\pi}}\,; \tag{28}$$

2) at $t_2 < t_K$

$$\begin{aligned}
P_{TT}(f,\tau) \approx f\Biggl\{ & I_s U_{TM}\sin\left(\frac{\pi t_0}{\tau}\right)\frac{(t_2-t_0)t_{K1}^2}{(t_{K0}+t_2-t_0)t_{K0}} + I_{TM}U_0\frac{\tau}{\pi}\left[\cos\left(\frac{\pi t_2}{\tau}\right)-\cos\left(\frac{\pi t_K}{\tau}\right)\right]+ \\
& + rI_{TM}^2\frac{t_{K1}^2}{2}\Biggl(\frac{t_K-t_2}{(t_{K0}+t_K-t_0)(t_{K0}+t_2-t_0)}+\frac{\cos(2\pi t_K/\tau)}{t_{K0}+t_K-t_0}-\frac{\cos(2\pi t_2/\tau)}{t_{K0}+t_2-t_0}+ \\
& + \frac{2\pi}{\tau}\sin\left(\frac{2\pi(t_0-t_{K0})}{\tau}\right)\left[Ci\left(\frac{2\pi(t_{K0}+t_K-t_0)}{\tau}\right)-Ci\left(\frac{2\pi(t_{K0}+t_2-t_0)}{\tau}\right)\right]+ \\
& + \frac{2\pi}{\tau}\cos\left(\frac{2\pi(t_0-t_{K0})}{\tau}\right)\left[Si\left(\frac{2\pi(t_{K0}+t_K-t_0)}{\tau}\right)-Si\left(\frac{2\pi(t_{K0}+t_2-t_0)}{\tau}\right)\right]\Biggr)\Biggr\},
\end{aligned} \tag{29}$$

where $Ci(x)$ - integral cosine , $Si(x)$ - integral sine.

The factor in expressions (26) and (29) at impulses frequency f, represents switching losses of a thyristor at its actuation.

2.2 Average power losses and losses at operation of a thyristor in a conducting state

At operation of a thyristor in a conducting state (при $t \geq t_{in}$) the average power of losses $P_{AV}(f,\tau)$ is determined by the expression:

$$P_{AV}(f,\tau) \approx f\int_{t_{in}}^{\tau} i(t)\,u(t)\,dt\,, \tag{30}$$

where dependences of time on anode current $i(t)$ and the voltage $u(t)$ are determined by formulas (21) and (22).

If we integrate (30), we get:

$$P_{AV}(f,\tau) \approx f\tau\left\{\frac{U_0 I_{TM}}{\pi}\left[1+\cos\left(\frac{\pi t_{in}}{\tau}\right)\right]+\frac{rI_{TM}^2}{2}\left[1+\frac{1}{2\pi}\sin\left(\frac{2\pi t_{in}}{\tau}\right)-\frac{t_{in}}{\tau}\right]\right\}. \tag{31}$$

2.3 Switching losses at a thyristor turning off

A thyristor turning off implies [1-4] the process of its transfer from on-state into off-state (nonconducting), when it is capable to stand a definite direct voltage, applied to it with the specified rate of rise dU/dt.

In the present article we shall assume, that the thyristor turning off is carried out via the power circuit by applying a reverse voltage to it.

A thyristor switchs to its on-state for the finit time required to dispers the extra charge stored in its layers. Thus the back current flows through the device, its dependence on the time is shown in a fig. 2, *a*

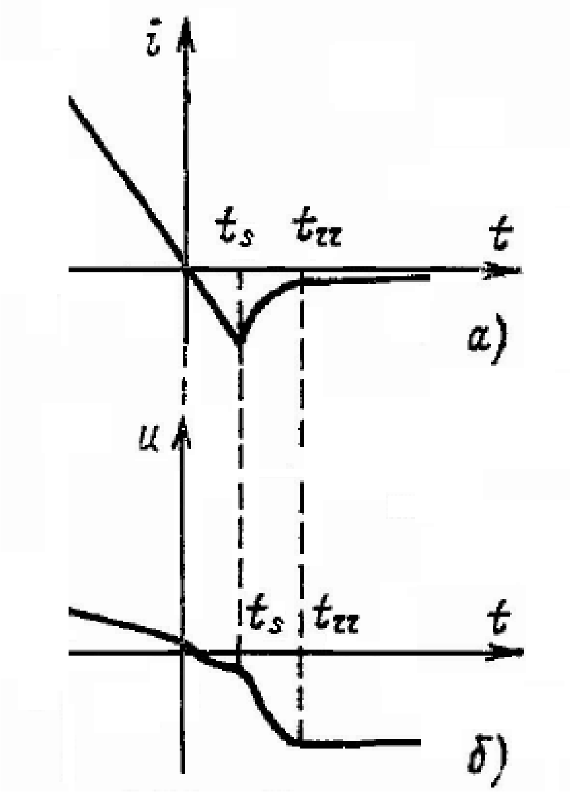

Fig. 2. Diagrams of current (a) and voltage (б)
at a thyristor turning off.

The time *t* in this figure is counted out from the moment, when the forward current through a thyristor becomes equal to zero. Down to this moment the forward current decreases up to zero point with the rate *di*/*dt*, determined by the voltage applied and parameters of external electric circuit. For the forward current sine pulse duration τ this rate is:

$$\frac{di}{dt} = -\frac{\pi I_{TM}}{\tau}. \qquad (32)$$

During the forward current decrease due to the mutual recombination of electrons and holes in semiconductor structure of a thyristor there is a decrease of stored extra charge. This process is inertial, and its rate depends, basically, on hole lifetime τ_p в *n*-базе ($\tau_p \approx 3 \div 6$ мкс [1]). Therefore to an instant $t = 0$ in base layers at *p*-*n*-interfaces the considerable extra charge is still remained, and at instant $t > 0$ the back current (fig. 2, a) starts to flow through a thyristor, with the same rate of rise as the rate of forward current fall:

$$i(t) = \frac{di}{dt}t = -\frac{\pi I_{TM}}{\tau}t. \qquad (33)$$

At this stage the structure of a thyristor practically does not block voltage as in its layers there is still enough number of extra carriers. Thus, the back current rise stage duration $t_s \approx 0{,}6 \div 0{,}7\tau_p$ [1]. Therefore at a thyristor switching to an active load the energy losses during this period of time with high degree of accuracy may be ignored. The flow of a back current through the structure promotes further decrease of extra carriers density, first, due to recombination processes, second, due to their knocking out by an external electric field. In the instant of time t_s the stored charge decreases so, that it starts to limit a back current. Thus the resistance of the device increases sharply, and it assumes an external voltage (14):

$$u(t) \approx -U_{TM} \sin\left(\frac{\pi t}{\tau}\right). \tag{34}$$

From this moment (the period t_s - t_{rr} in fig. 2, a) with the decrease of extre charge density the back current passing through a thyristor decreases sharply from its maximum value I_{rr} practically up to zero point [2]:

$$i(t) \approx -I_{rr} \exp\left(-\frac{t-t_s}{0{,}53\, t_f}\right), \tag{35}$$

where t_f - the time, which is usually considered as the final stage of a thyristor resistance recovery duration (fig. 3).

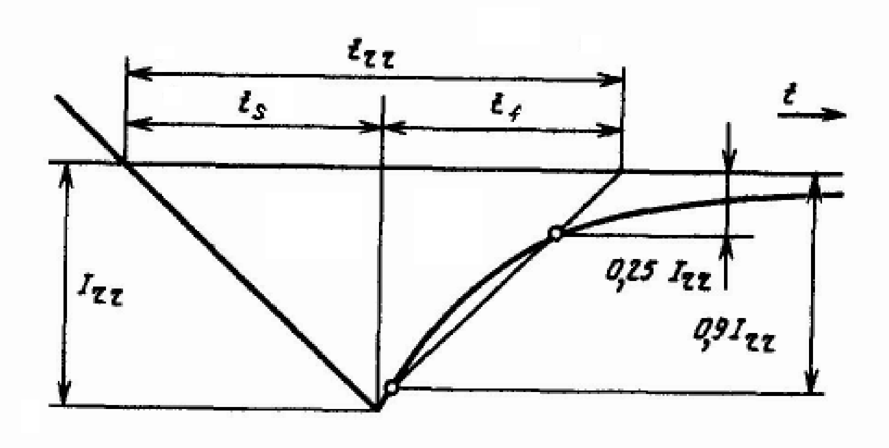

Fig. 3. A standard method of back current curve approximation

As it follows from the formula (33) the maximum back current value

$$I_{rr} = \frac{\pi I_{TM}}{\tau} t_s. \tag{36}$$

Taking into account, that an average power of switching losses at a thyristor turning off

$$P_{RQ}(f,\tau) \approx f \int_{t_s}^{\infty} i(t)\, u(t)\, dt, \tag{37}$$

using expressions (34)-(36) we derive

$$P_{RQ}(f,\tau) \approx f\, \frac{\pi\tau t_s t_f I_{TM} U_{TM}}{(\tau^2+\pi^2 t_f^2)\cdot(4\tau^2+\pi^2 t_f^2)} \left\{3\pi\tau_f \cos\left(\frac{\pi t_s}{\tau}\right) + (2\tau^2-\pi^2 t_f^2)\sin\left(\frac{\pi t_s}{\tau}\right)\right\}. \tag{38}$$

It should be noted, that back current rise time t_s and its fall time depend essentially on the forward current amplitude, which flows before a thyristor turning off, on the rate

di/dt of its change and on the temperature T_j of semiconductor structure. As our study demonstrates, for the wide class of devices this dependence is described by these empirical formulas:

$$t_s(I_{TM}, di/dt, T_j) = t_{s0}\left(\frac{I_{TM}}{I_0}\right)^{\alpha_s}\left(\frac{(di/dt)_0}{di/dt}\right)^{(\beta_s I_{TM})^{-0,25}}\left(\frac{T_j}{T_{j0}}\right)^{3/2}, \qquad (39)$$

$$t_f(I_{TM}, di/dt, T_j) = t_{f0}\left(\frac{I_{TM}}{I_0}\right)^{\alpha_f}\left(\frac{(di/dt)_0}{di/dt}\right)^{(\beta_f I_{TM})^{-0,2}}\left(\frac{T_j}{T_{j0}}\right)^{3/2}, \qquad (40)$$

where α_s, α_f, β_s, and β_f - experimentally determined parameters of a model, which depend only on design features of PSC device, and t_{s0} and t_{f0} - back current rise time and fall time accordingly measured at the temperature T_{j0} of semiconductor structure, at value I_0 of classification current, which drops with the rate $(di/dt)_0$ at PSC switching from conducting state to a nonconducting state.

The expression (38) together with (39) and (40) determines completely an average power of switching losses and losses [the factor at f in (38)] at a thyristor turning off.

The average power of total losses $P(f,\tau)$ is determined by formulas (2), (26) - (29), (31) and (38).

As these formulas demonstrate, the average power of total losses is proportional to the current pulse repetition rate. Thus losses themselves $E = P/f$ do not depend on frequency and at given current amplitude are determined by pulse duration τ only.

Graphs of total losses dependence versus forward current sine pulses duration constructed on the basis of obtained formulas for a thyristor MT3-500 under different values of a current I_{TM}, are shown in a fig.4 (continuous curves) . In the same figure graphs of switching losses are figured at a device turning on (dotted curves) and a device turning off (chain curves), and also graphs of losses by a thyristor operation in on-state (dashed curves).

The analysis of constructed graphs demonstrates, that in area of sufficiently large τ losses in thyristors are conditioned, basically, by losses at their operation in conducting state. The switching losses in this area of pulses duration may be neglected.
With the decrease of τ, at operation in a conducting state losses also drop, and switching losses, quite the contrary, grow and at duration $\tau \sim 200 \div 300$ mcs are comparable with losses by a thyristor operation in on-state.

At $\tau < 200 \div 300$ mcs switching losses at the device turning off dominate. In this area of τ, losses at a thyristor turning on and losses by its operation in a conducting state quickly decrease due to that the pulse duration becomes comparable with the turn-on time of the device. Therefore forward current pulses, in the strict sence, cease to be sinusoidal. Their rise-up portions are distorted heavily under the influence of the turning on transients.

At last, when the pulse duration becomes equal to a turn-on timeof the device ($\tau \sim 5 \div 7$ mcs), it ceases to be turned on completely. At smaller τ losses of a thyristor are conditioned, basically, by leakage currents passing through the device.

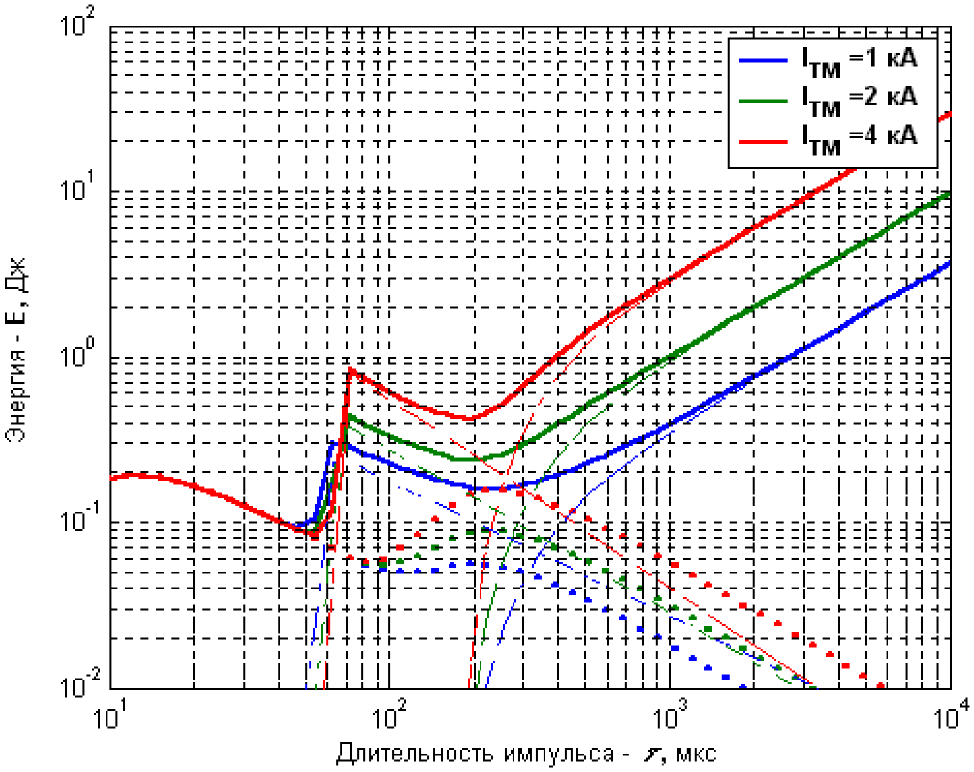

Fig. 4. Losses of a thyristor MT3-500 depending on forward current sine pulses duration τ (U_{TM} = 1280 B, T_j = 398 K, T_c = 298 K): continuous curves - total losses; dotted curves - switching losses at the device turning on; chain curves- loss at the device turning off; dashed curves - loss by a thyristor operation in on-state.

3 Frequency dependence of sine current pulses amplitude in stationary conditions of a thyristor operation

In an implicit form the frequency dependence of forward current sine pulses amplitude in stationary conditions of a thyristor operation is set by equation (1), in which an average power of losses $P(f,\tau)$ is determined by expressions (2), (26) - (29), (31) and (38).

The graphs of this dependence (level lines) constructed for different values of a current I_{TM}, flowing through a thyristor MT3-500, are shown in fig. 5.

Unfortunately, to obtain explicit expressions for the function $I_{TM}(f,\tau)$ is proved to be difficult. It is possible only in one particular case - at $\tau >> t_{in}$, t_{rr}, when switching losses at a thyristor operation may be neglected. In this case

$$I_{TM}(f,\tau) \approx \frac{2U_0}{\pi r}\left\{\sqrt{1+\frac{\pi^2 r}{2f\tau}\,\frac{T_j-T_c}{R_{th}U_0^2}}-1\right\}. \qquad (41)$$

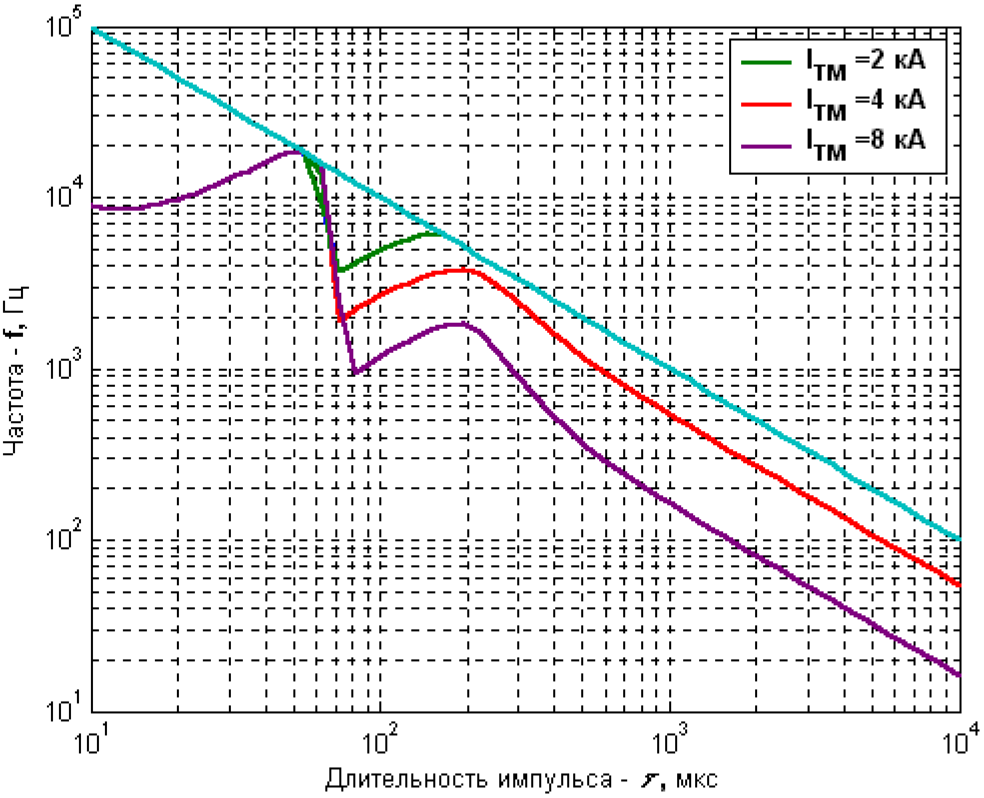

Fig. 5. Frequency response curves of a thyristor MT3-500, constructed for sine current pulses under following conditions:
U_{TM} = 1280 B, T_j = 398 K, T_c = 298 K. A straight line in this figure corresponds to continuous mode of a thyristor operation, when $f = 1/\tau$.

4 Losses and an average power of losses in power semiconductor diodes

As against thyristors, the actuation of power semiconductor diodes is carried out practically immediatelly, as the process of their conductivity modulation is finished for several tens microseconds [1, 2]. Thus the physical processes flowing in diodes by their operation in a conducting condition and at their switching from conducting to nonconducting condition, practically do not differ from those processes, which flow in semiconductor thyristors. Thus, the energy losses at diodes operation are formed from losses in the term of their operating in on state and switching losses at their turning off:

$$P(f,\tau) = P_{AV}(f,\tau) + P_{RQ}(f,\tau)\,. \qquad (42)$$

The average power of losses at diodes operation in a conducting state is determined by expression (31), in which the turn-on time t_{in}should be put as equal to zero:

$$P_{AV}(f,\tau) \approx f\tau \left\{ \frac{2U_0 I_{TM}}{\pi} + \frac{r I_{TM}^2}{2} \right\}. \qquad (43)$$

An average power of switching losses at switching of diodes from the forward to the reverse direction may be calculated under the formula (38), in which a back current rise time t_s and a time of its fall t_f are set by expressions (39) and (40).

Formulas (42), (43) and (38) - (40) completely determine an average power of total losses $P(f,\tau)$ and total losses $E = P/f$ in power semiconductor diodes.

As well as in case of thyristors the average power of total losses in diodes appears proportional to a current pulse repetition rate. Thus losses do not depend on frequency and at given amplitude of a current are determined by a pulse duration τ. only.

Graphs of total losses versus forward current sine pulses duration constructed for a diode ДЛ-343-630-34 under different values of a current I_{TM}, are shown in a fig. 6 (continuous curves). In the same figure graphs of switching losses are figured at the device turning off (chain curves), and also graphs of losses at the diode operation in on-state (dashed curves).

As this figure demonstrates, at sufficiently large τ the main contribution to losses of diodes is energy losses (43) at operation in on-state. With the decrease of τ these losses drop practically linearly and at small τ become less than losses (38) at switching of diodes from the forward to the reverse direction.

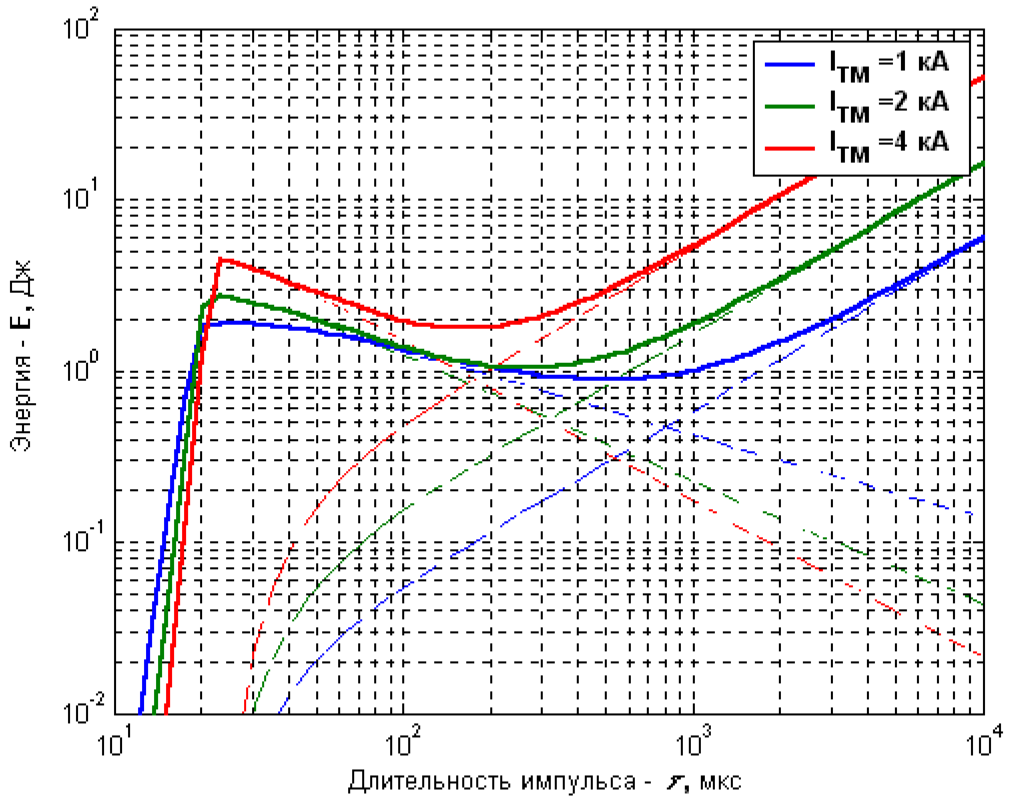

Fig. 6. Losses of the diode ДЛ-343-630-34 versus duration τ f of forward current sine pulses (U_{TM} = 1280 B, T_j = 398 K, T_c = 298 K): Continuous curves - total losses; dotted curves- switching losses at

the device turning on; chained curves- loss at the device turning off.

Thus, at small durations of current pulses flowing through diodes, their losses, as well as the losses of thyristors, are conditioned, basically, by switching losses at their turning off.

At τ, equal to several tens microseconds (fig. 6), diodes cease to work normally, as the pulse duration becomes comparable with the time of conductivity modulation at devices operation or with the time $t_{rr}$of back resistance recovery.

5 Frequency dependences of amplitude of sinusoidal current pulses in steady-state conditions of activity of the diode

In an implicit form the frequency dependence of forward current sine pulses amplitude in stationary conditions of the diode operation is set by equation (1), in which an average power of losses $P(f,\tau)$ is determined by expressions (42), (43) and (38). At $\tau >> t_{rr}$, when switching losses at the diode activity may be neglected, this dependence may be shown in the explicit form (41).

Graphs $I_{TM}(f,\tau)$ (level lines) constructed for different values of a current I_{TM}, flowing through the diode ДЛ-343-630-34, are shown in fig. 7.

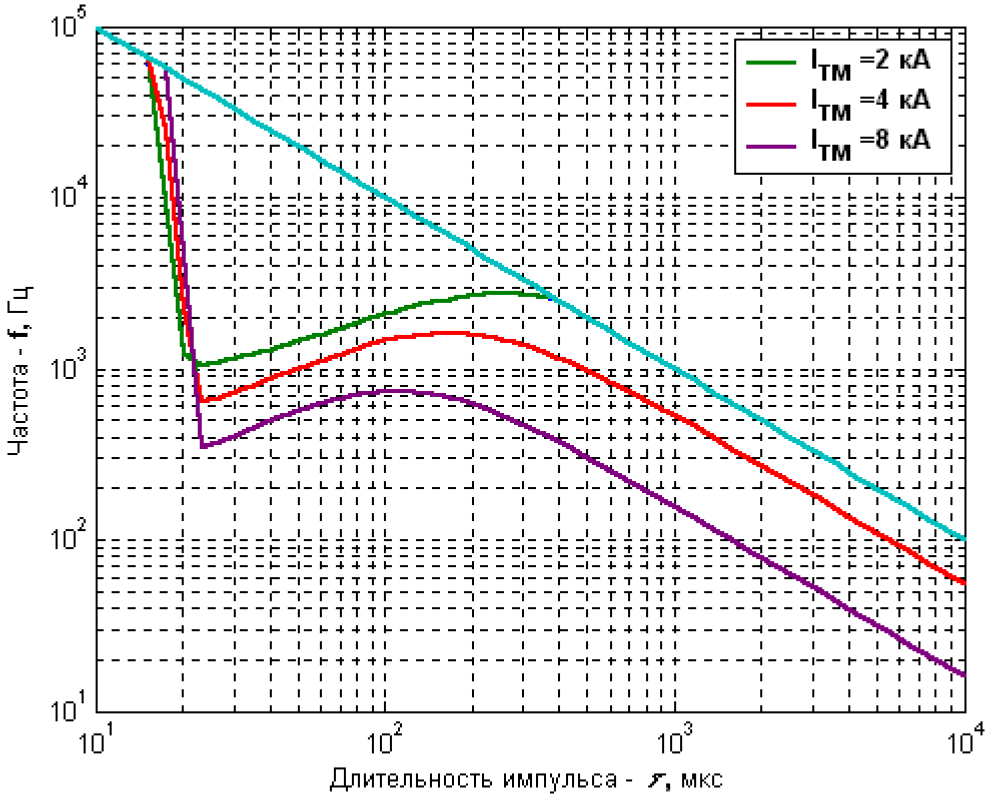

Fig. 7. Frequency response curves of the diode ДЛ-343-630-34, constructed for sine current pulses under following conditions:
U_{TM} = 1280 B, T_j = 398 K, T_c = 298 K. A straight line in this figure corresponds to continuous mode of operation of the diode, when $f = 1/\tau$.

6 Conclusion

Results, obtained in at present study, demonstrate, that frequency response curves of diodes and thyristors are determined by such energy losses, which are evolved in semiconductor structures of PSC device by way of heat. At large durations of pulses these frequency response curves are conditioned basically by losses of energy at devices operation in conducting state. In this case this frequency dependence of sine current pulses amplitude may be expressed by the formula (41). At small durations of pulses, frequency response curves of diodes and thyristors are conditioned, basically, by energy losses at devices switching from conducting to a non-conducting state.

Comparison of frequency response curves of diodes and thyristors demonstrates that main differences are connected with switching energy losses at thyristors turning on. These losses influence on dynamic properties of thyristors in area of pulses durations $\tau \sim$ 200 ÷ 300 mcs and also result in distortion of rise-up portion of forward current pulses . The analysis of frequency response curves of diodes and thyristors allows us to conclude, that for improvement of dynamic properties of PSC devices it is necessary, first of all to minimize energy losses at devices operation in a conducting state (43) as well as at their switching from conducting to non-conducting state (38).

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