ON THE PROPER COORDINATION OF FUSES WITH SEMICONDUCTOR DEVICES IN THE HEAVY SHORT-CIRCUIT REGION

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INTRODUCTION The maximum permissible current ratings of diodes and thyristors at short-circuits are characterized by manufacturers in the form of the I^2t parameter which is a non--repetitive survival rating for 10 ms overload. Appropriate correction factors are given for current faults of a shorter duration than 10 ms. This interferes with the until quite recently accepted condition for diodes and thyristors at short--circuits of a shorter duration than 10 ms, in which case $I^2t = const.$ was recommended to be assumed. After subjecting the I^2t parameter to consideration for a shorter duration than 10 ms it may be easily concluded that the condition I^3t or I^4t = constant would be more suitable.

The manufacturers of thyristors and diodes also determine the value of the I^2t parameter for fault currents having a sinusoidal wave shape. For $i(t) = I_m \sin\omega t$:

$$I^2t = \int_0^{T/2} [i(t)]^2 dt = \frac{1}{2} I_m^2 \left(\frac{T}{2}\right) \qquad (1)$$

In view of the changing character of the I^2t/Th versus time it is possible to determine the power x for the I^xt expression, for which it will be constant for the given type of the thyristor/diode on the basis of the following condition:

$$\left(\sqrt{\frac{2(I^2t)_1}{\frac{T_1}{2}}}\right)^x \cdot \frac{T_1}{2} = \left(\sqrt{\frac{2(I^2t)_2}{\frac{T_2}{2}}}\right) \cdot \frac{T_2}{2}$$

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thus

$$x = 2\,\frac{\log \frac{T_1}{T_2}}{\log\left[\frac{(I^2t)_2}{(I^2t)_1}\cdot\frac{T_1}{T_2}\right]} \qquad (2)$$

For instance, in the case of a certain thyristor its manufacturer gave as follows: $(I^2t)_1 = 1.45\times10^6\ A^2s$ for $T_1/2 = 10^{-2}$ s and $(I^2t)_2 = 0.45\times10^6\ A^2s$ for $T_2/2 = 10^{-3}$ s. Thus, on the basis of (2) we have:

$$x = 2\,\frac{\log \frac{10^{-2}}{10^{-3}}}{\log \frac{0{,}45\cdot10^6}{1{,}45\cdot10^6}\cdot\frac{10^{-2}}{10^{-3}}} = 4{,}06$$

Therefore, it may be assumed that the dependence $I^4t = const$ is justifield for $t < 10^{-2}$ s.

It is possible to determine I^4t or I^3t parameter in the function of the I^2t parameter found for $\frac{T}{2}$ from the following formulae:

for n = 3

$$I^3t = \int_0^{T/2} i^3dt = \frac{4}{3\pi}I_m^3\left(\frac{T}{2}\right) \cong 1{,}19\left(I^2t\right)^{3/2}\left(\frac{T}{2}\right)^{-\frac{1}{2}} \qquad (3)$$

for n = 4

$$I^4t = \int_0^{T/2} i^4dt = \frac{3}{8}I^4\frac{T}{2} = 1{,}5\left(I^2t\right)^2\left(\frac{T}{2}\right)^{-1} \qquad (4)$$

As to short circuits with heavy duty prospective conditions the damping resistance (Fig.1a) may be neglected for the accretion phase of the current.

Thus,

$$i_{(SC)}(t) = I_m \sin\omega t \qquad (5)$$

when only the symmetrical current (SC) component appears, or

$$i_{(ASC)}(t) = I_m (1 - \cos \omega t) \qquad (6)$$

at maximum asymmetry and lack of short-circuit damping (ASC = = asymmetrical current).
With regard to the two cases of the short-circuit current wave shape further consideration will be given to calculate true current exposures due to the operation of a fuse as expressed in the third or fourth power.

Extensive studies devoted to fuses designed for the protection of diodes and thyristors have shown that:

- the arc ignition moment is practically equal to the moment at which the limited current appears,
- after arc ignition the current remaines at an approximately constant value and practically falls down to zero at the moment of natural commutation of the supply voltage.

The course of the current in such a circuit as shown in Fig.1 and under the above given conditions is shown in Fig.2.

The manufacturer of fuses determines the value of the so-called pre-arcing integral $I^2t = \int_0^{t_p} i_p^2\, dt$. In dependence on the symmetrical component of the amplitude of the prospective short-circuit current usually one determins the so-called virtual pre-arcing time

$$t_{vp}^{(2)} = \frac{\int_0^{t_p} i_p^2\, dt}{I_m^2} \qquad (7)$$

Within the function of that value the true prearcing time t_p was determined for the currents according to (5) and (6) in the from of diagrams in Fig.3a. As to the pre-arcing time, Fig.3b, the relative value has been determined for the limited current in relation to amplitude of the symmetrical short-circuit current. With the application of the curves in Fig.3c value of the virtual arcing time $t_{va}^{(n)}$ have been described to these values for various values of the power exponent for such current, for which the current exposure at fuse operation is intended to be determined. The virtual arcing time has been determined under the assumption of the relative value of the arc current:

$$k_{ia} = \frac{i_a}{i_l} \qquad (8)$$

as follows:

$$t_{va}^{(n)} = \frac{\int_{t_p}^{t_a} i_a^n \, dt}{I_m^n} \cdot \frac{1}{k_{ia}^n} \qquad (9)$$

where:

n - power exponent n = 2, 3, 4 ;

(n) - exponent index for the power for which the calculation has been made.

PROPOSED METHOD FOR THE SELECTION OF SHORT-CIRCUIT PROTECTION FOR DIODES AND THYRISTORS

I. To determine for a given type of diode/thyristor the exponent x for the current power in campliance with formula (2) and to round it off to the closest natural number n = 2, 3 or 4.

II. First to select a fuse for a thyristor/diode e.g. in compliance with the till known criterion

$$I^2t\big|_{Th} \geqslant I^2t\big|_{Fuse\ Total} \qquad (10)$$

III. To read in the fuse - catalogue the declared value of the Pre-arcing $I^2t = \int_0^{t_p} i^2 dt$.

IV. To calculate, from the date relating to the short-circuit the maximum value of short-circuit symmetrical current:

$$I_m = \sqrt{2}\, I_{(RMS)(prosp.\ current)} \qquad (11)$$

V. To calculate, according to formula (7), the virtual pre-arcing time $t_{vp}^{(2)}$ for the fuse.

VI. To take from the diagrams in Fig.3a for the calculated $t_{vp}^{(2)}$ time according to item (V) the real pre-arcing time t_p

for the symmetrical current $t^{(2)}_{p(SC)}$ and the asymmetrical current $t^{(2)}_{p(ASC)}$.

VII. For the t_p as read off in (VI) take the value of the relative limited current $\frac{i_l}{I_m}(SC)$ and $\frac{i_l}{I_m}(ASC)$ from Fig.3b.

VIII. Take the virtual arcing time for $n = 2$: $t^{(2)}_{va(SC)}$ and $t^{(2)}_{va(ASC)}$ from Fig.3c for the values $\frac{i_l}{I_m}$ read according to item (VII).

IX. On the basis of the catalogue data for the fuses, calculate the value:

$$\text{Arcing } I^2t = \int_0^{t_a} i_a^2 \, dt = \text{Total } I^2t - \text{Pre-arcing } I^2t \tag{12}$$

X. Calculate, for the smaller of the $t^{(2)}_{va}$ values calculated according to (VIII), and the Arcing I^2t value according to (IX), the relative arc current value by transforming the equation (9):

$$k_{ia} = \frac{i_a}{i_l} = \sqrt{\frac{\text{Arcing } I^2t}{t^{(2)}_{va} \, I_m^2}} \tag{13}$$

XI. According to exponent n from (I), and to $\frac{i_l}{I_m}$ from (VII), read from Fig.3c the value of $t^{(n)}_{va(SC)}$ and $t^{(n)}_{va(ASC)}$

XII. Calculate the value of the arc integral according to cryterion $I^n t$ = const. from the dependence:

$$\text{Arcing } I^n t = \int_{t_p}^{t_a} i_a^n \, dt = (k_{ia} I_m)^n \, t^{(n)}_{va} \tag{14}$$

for the bigger of the $t^{(n)}_{va}$ values read off according to (XI).

XIII. For the calculated, according to (V), virtual pre-arcing time t_{vp} for the I^2t = constant cryterion, carry out recalculation for the exponent n as assumed according to (I) in compliance with the curves given in Fig.3d.

XIV. Calculate for the $t^{(n)}_{vp}$ as calculated according to (XIII) the value:

$$\text{Pre-Arcing } I^n t = \int_0^{t_p} i_p^n \, dt = I_m^n \, t^{(n)}_{vp} \tag{15}$$

XV. Calculate the fuse total integral on the basis of the dependence:

$$\text{Total } I^n t = \text{Pre-Arc. } I^n t \text{ (acc. to XIV)} + \text{Arc. } I^n t \text{ (acc. to XII)} \quad (16)$$

XVI. Recalculate the catalogue value of I^2t for the thyristor/diode for the n exponent as determined according to (I) in compliance with Fig.4 or according to the dependence (3) or (4).

XVII. Check, if the condition (17) has been complied with:

$$I^n t/_{Th} \text{ (acc. to XVI)} \overset{if}{>} \text{Total } I^n t/_F \text{ (acc. to XV)} \quad (17)$$

If so, it is safe to assume, that the selected fuse protects the diode/thyristor against the short-circuit current. If the above given condition is not complied with, however, it is necessary either to select a diode/thyristor of a higher warranted value of its I^2t, or a fuse having a smaller total integral, and above all of a lower prearcing integral. In such case the checking cycle according to the above described algorithm is to be repeated.

CONCLUSIONS There is no doubt that the I^2t parameter is not a constant value for semiconductors in the region of short-circuit current. In addition, it is determined that such wave-shape of short-circuit currents never appears in 50 (60) Hz networks. From the catalogue data for the diode/ /thyristors it follows that the $I^3t = \int i_T{}^3 \, dt$, or $I^4t = \int i_T^4 \, dt$ = const. value is more true. This makes recalculation necessary of the fuse short-circuits parameters. Suitable dependences and diagrams are given in this paper. The proposed method is more universal than the thus far applied one. It stresses the effect of the short-circuit current value which is more significant than its duration.

In the example given in the appendix it was demonstrated, that a fuse that had been selected in compliance with the classical method does not fulfil the requirements for correct protection according to the proposed method.

APPENDIX. EXAMPLE FOR THE SELECTION OF SHORT-CIRCUIT PROTECTION FOR A THYRISTOR BY A FUSE

Classical method for short-circuit current protection.

Thyristor data: $I_{T(AV)} = 65$ A, $I_{T(RMS)} = 100$A

$(I^2t)_1 = 5.5\times10^3$ A^2s, $T_1/2 = 10^{-2}$ s

$(I^2t)_2 = 4.1\times10^3$ A^2s, $T_2/2 = 3\times10^{-3}$ s

Fuse data: $I_{F(RMS)} = 100$ A

Pre-arcing $I^2t = 10^3$ A^2s, Total $I^2t = 4.6\times10^3$ A^2s

The "classical" condition for short-circuit protection the thyristor by the fuse with the above given data is complied with:

$$I^2t/_{Th} = 5.5\times10^3\ A^2s > I^2t/_{Ftotal} = 4.6\times10^3\ A^2s$$

Proposed method for short-circuit current protection.

I. From the thyristor catalogue data,(acc.to 2), we have:

$$x = 2\times\frac{\log\frac{10^{-2}}{3\times10^{-3}}}{\log\frac{4.1\times10^3}{5.5\times10^3}\times\frac{10^{-2}}{3\times10^{-3}}} = 2.65$$

Assumed: n = 3.

II, III. The following has been assumed in compliance with the previous exemple: $I_{F(RMS)} = 100$ A, Pre-Arcing $I^2t = 10^3$ A^2s; Total $I^2t = 4.6\times10^3$ A^2s.

IV. The following has been obtained from the short-circuit data: $I_m = \sqrt{2}\times I_{(RMS)}$ (prosp.current) $= \sqrt{2}\times70\times10^3 = 10^5$ A.

V. $$t_{vp}^{(2)} = \frac{\text{Pre-Arcing } I^2t}{I_m^2} = \frac{10^3}{(10^5)^2} = 10^{-7}\ s.$$

VI. For $t_{vp}^{(2)}$ (acc.to V) $= 10^{-7}$ s $\xrightarrow{\text{Fig.3a}}$ $t_{p(SC)} = 0.13\times10^{-3}$ s;

$t_{p(ASC)} = 0.77\times10^{-3}$ s.

VII. For $t_{p(SC)}$ (acc. to VI) $\xrightarrow{\text{Fig.3b}}$ $\frac{i_1}{I_m}$ (SC) $= 5 \times 10^{-2}$;

$\frac{i_1}{I_m}$ (ASC) $= 3 \times 10^{-2}$.

VIII. For $\frac{i_1}{I_m}$ (acc. to VII) $\xrightarrow{\text{Fig.3c}}$ $t^{(2)}_{va(SC)} = 2 \times 10^{-5}$ s;

IX. Acc. to (12):

Arcing I^2t = Tot. I^2t - Pre-Arc. $I^2t = 4.6 \times 10^3 - 10^3 = 3.6 \times 10^3\ A^2s$

X. Acc. to (13):

$$k_{ia} = \frac{i_a}{i_1} = \frac{\text{Arcing } I^2t}{t^{(2)}_{va} \times I^2_m} = \frac{3.6 \times 10^3}{1.8 \times 10^{-5} \times (10^5)^2} \cong 0.14$$

XI. For n (acc.to I) = 3, $\frac{i_1}{I_m}$ (acc. to VII) $\xrightarrow{\text{Fig.3c}}$

$t^{(3)}_{va}(SC) = 7 \times 10^{-7}$ s ; $t^{(3)}_{va}(ASC) = 3 \times 10^{-7}$ s.

XII. For k_{ia} (acc.to X), I_m (acc.to IV), $t^{(3)}_{va(max)}$ (acc.to XI) we calculate:

Arcing $I^3t = k_{ia} \times I^3_m \times t^{(3)}_{va(max)} = 0.14 \times (10^5)^3 \times 7 \times 10^{-7} = 1.9 \times 10^6\ A^3s$

XIII. For $t^{(2)}_{vp}$ (acc. to V), and n (acc. to I) $\xrightarrow{\text{Fig.3d}}$

$t^{(3)}_{vp}(SC) = 7 \times 10^{-9}$ s; $t^{(3)}_{vp}(ASC) = 4.8 \times 10^{-9}$ s.

XIV. For $t^{(3)}_{vp(max)}$ (acc. to XIII); I_m (acc.to V) and n (acc.to I) we calculate:

Pre-Arcing $I^3t = t^{(3)}_{vp(max)} \times I^3_m = 7 \times 10^{-9} \times (10^5)^3 = 7 \times 10^6\ A^3s$

XV. For Pre-Arcing I^3t (acc.to XIV) and Arcing I^3t (acc.to XII) we calculate:

Total I^3t = Pre-Arcing I^3t + Arcing $I^3t = 7 \times 10^6 + 1.9 \times 10^6 =$
$= 8.9 \times 10^6\ A^3s$.

XVI. For n (acc.to I), and the value of the thyristor I^2t (acc. to I) $\xrightarrow{\text{Fig.4}}$ $I^3t/_{Th} = 5 \times 10^6\ A^3s$

XVII. The condition (17) has not been complied with:

$I^3t/_{Th}$ (acc.to XVI) $= 5 \times 10^6\ A^3s \overset{NO!}{>}$ Total I^3t_{Fuse} (acc.to XV) $=$
$= 8.9 \times 10^6\ A^3s$

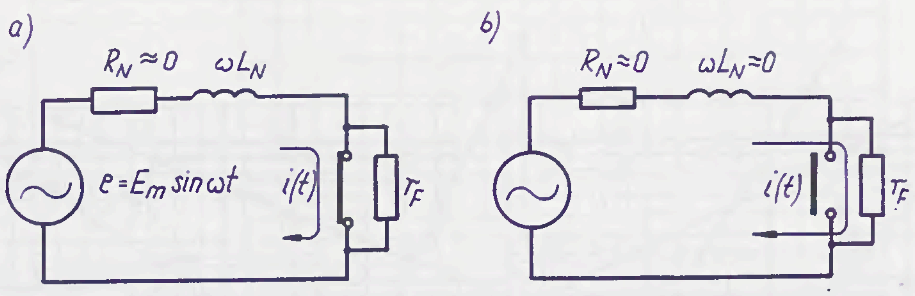

Fig.1. Substitute diagram for a short-circuit with a fuse operating: a) in the prearcing time, b) during the arc burning time.

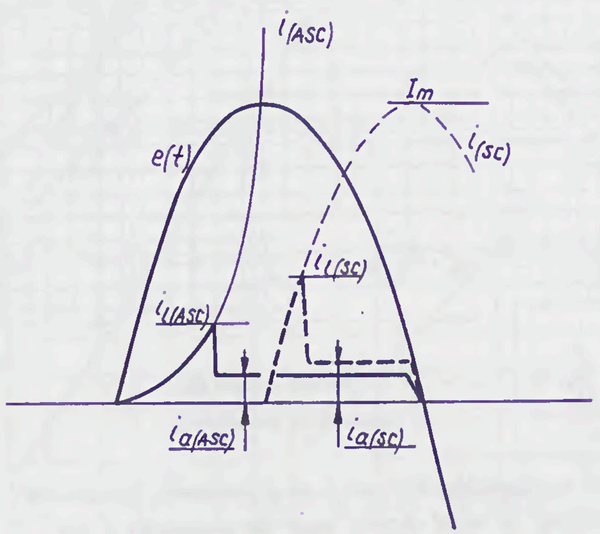

Fig.2. Short-circuit current limited by a fuse: $i_{(SC)}$ - symmetrical current, $i_{(ASC)}$ - asymmetrical current.

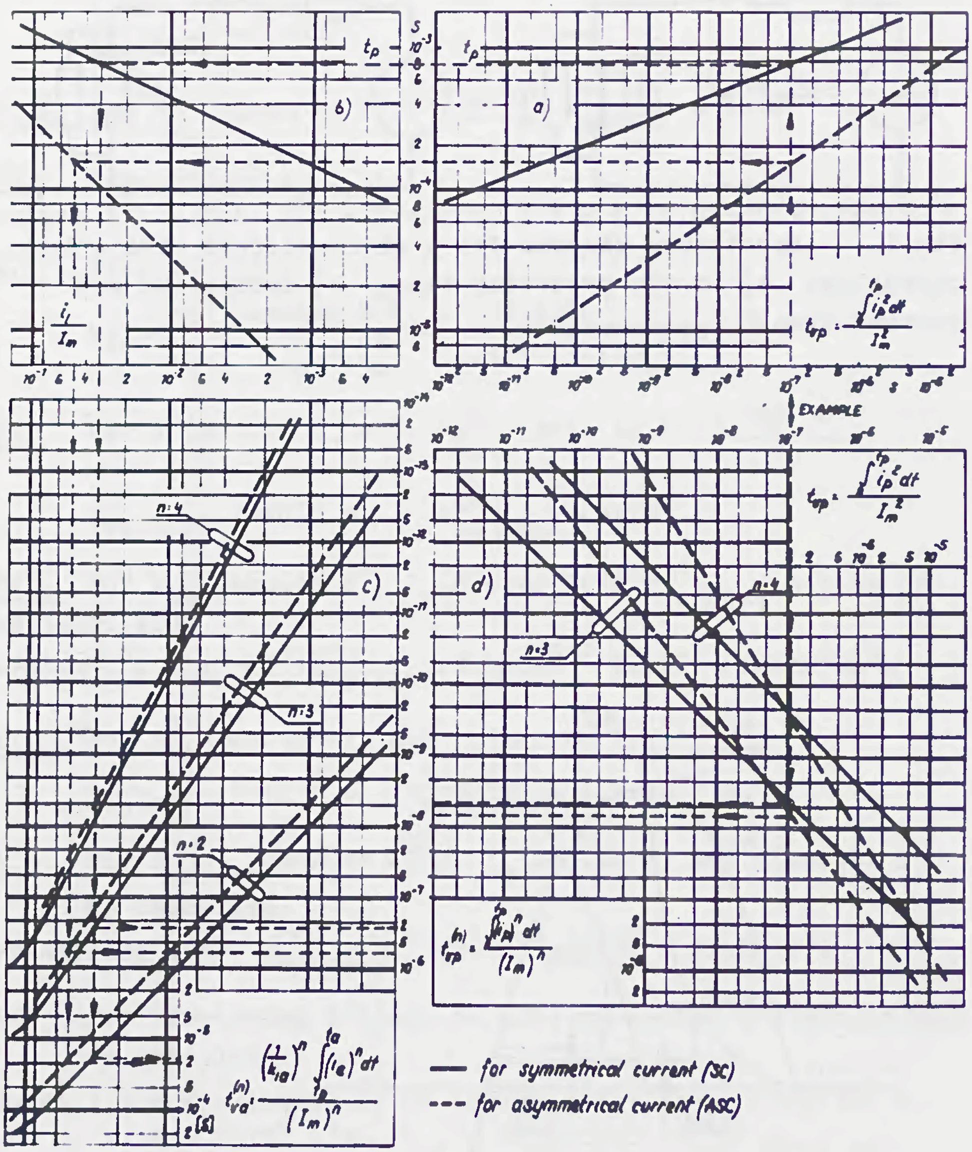

Fig.3. Diagrams for recalculating the values of characteristic parameters of a fuse operating at short-circuits under the assumption of the $I^n t = \int i^n dt$

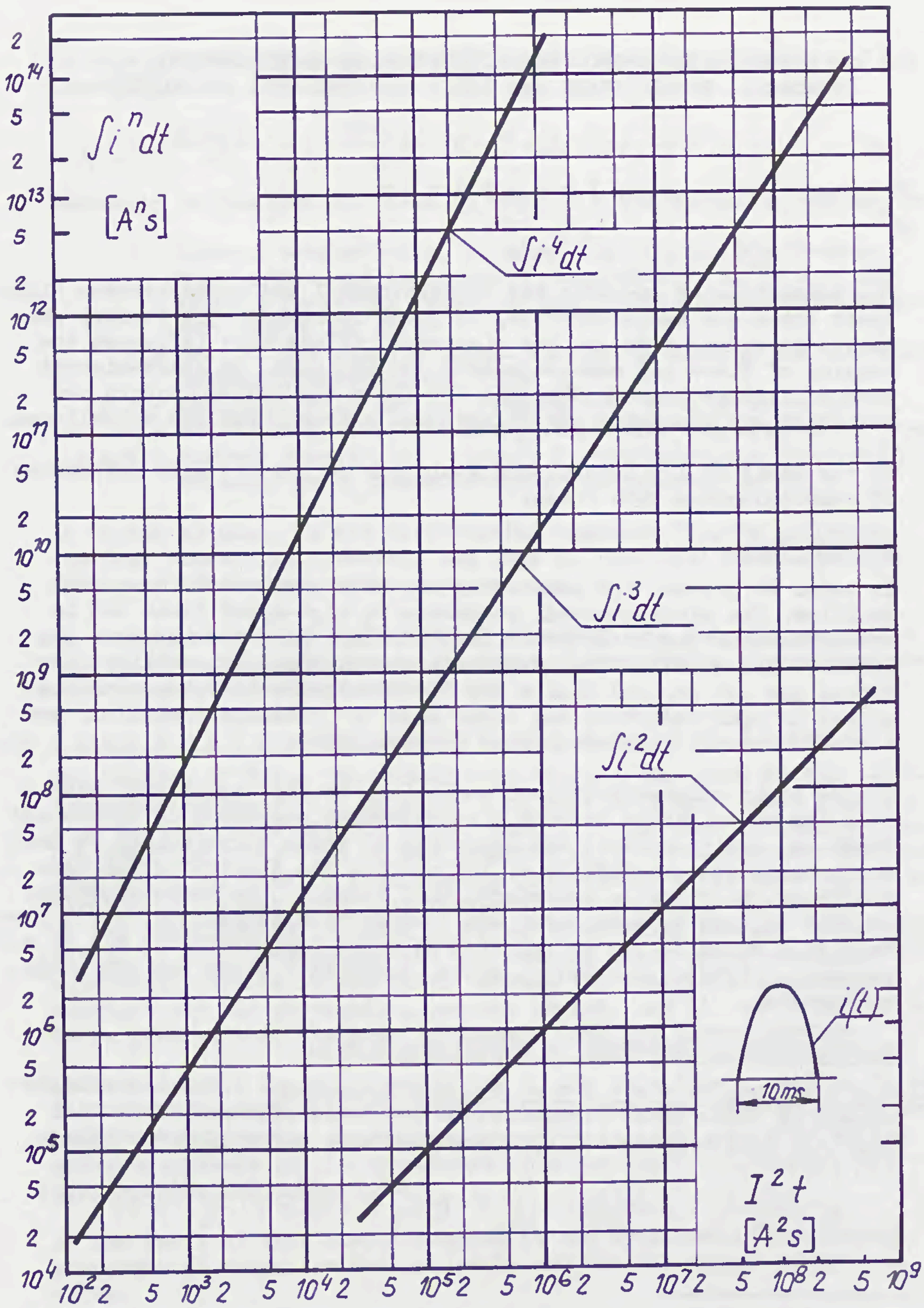

Fig.4. Dependence of the $I^2t = \int (I_m \cdot \sin\omega t)^n dt$ versus the value of the I^2t for $T/2 = 10^{-2}$ s.