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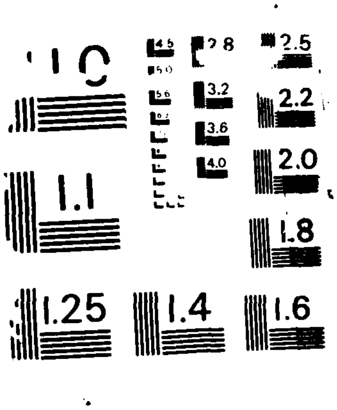

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# FOREIGN TECHNOLOGY DIVISION



## SELF-EXCITATION OF A SINGLE PHASE INDUCTION PULSE-EXCITED GENERATOR

by

Yu. A. Romanov, G. A. Sipaylov



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# EDITED TRANSLATION

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SELF-EXCITATION OF A SINGLE PHASE INDUCTION PULSE-EXCITED GENERATOR

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## U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

| Block | Italic | Transliteration | Block | Italic | Transliteration |
|---|---|---|---|---|---|
| А а | *А а* | A, a | Р р | *Р р* | R, r |
| Б б | *Б б* | B, b | С с | *С с* | S, s |
| В в | *В в* | V, v | Т т | *Т т* | T, t |
| Г г | *Г г* | G, g | У у | *У у* | U, u |
| Д д | *Д д* | D, d | Ф ф | *Ф ф* | F, f |
| Е е | *Е е* | Ye, ye; E, e* | Х х | *Х х* | Kh, kh |
| Ж ж | *Ж ж* | Zh, zh | Ц ц | *Ц ц* | Ts, ts |
| З з | *З з* | Z, z | Ч ч | *Ч ч* | Ch, ch |
| И и | *И и* | I, i | Ш ш | *Ш ш* | Sh, sh |
| Й й | *Й й* | Y, y | Щ щ | *Щ щ* | Shch, shch |
| К к | *К к* | K, k | Ъ ъ | *Ъ ъ* | " |
| Л л | *Л л* | L, l | Ы ы | *Ы ы* | Y, y |
| М м | *М м* | M, m | Ь ь | *Ь ь* | ' |
| Н н | *Н н* | N, n | Э э | *Э э* | E, e |
| О о | *О о* | O, o | Ю ю | *Ю ю* | Yu, yu |
| П п | *П п* | P, p | Я я | *Я я* | Ya, ya |

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

## RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

| Russian | English | Russian | English | Russian | English |
|---|---|---|---|---|---|
| sin | sin | sh | sinh | arc sh | $\sinh^{-1}$ |
| cos | cos | ch | cosh | arc ch | $\cosh^{-1}$ |
| tg | tan | th | tanh | arc th | $\tanh^{-1}$ |
| ctg | cot | cth | coth | arc cth | $\coth^{-1}$ |
| sec | sec | sch | sech | arc sch | $\operatorname{sech}^{-1}$ |
| cosec | csc | csch | csch | arc csch | $\operatorname{csch}^{-1}$ |

| Russian | English |
|---|---|
| rot | curl |
| lg | log |



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# SELF-EXCITATION OF A SINGLE PHASE INDUCTION PULSE-EXCITED GENERATOR

Yu.A. Romanov, G.A. Sipaylov

The question of the power feed of electromagnets which require high reserves of reactive energy takes on great urgency with the development and creation of powerful accelerators of charged particles. Both a continuous and pulsed power feed of the apparatuses is possible. Both forms of power supply can be accomplished if as the storage devices of reactive energy, capacitive banks or electrical machine apparatuses are used. In the development of electric-machine energy storage devices with the use of synchronous and homopolar generators, attention began to be paid to the induction [asynchronous] machine.

Investigations on the use of induction generator in pulsed systems for the charging of capacitors are at present being conducted. The experimental works carried out in this direction are indicative of the propect of similar synthetic schemes [1]. Indicated in work [2] is the expediency of the use of the induction generator with a capacitve excitation as the source of high pulse powers, and examined is the possibility of the complete conversion of kinetic energy of the rotating masses into electromagnetic energy during one pulse.

Thus the possibility of using induction generators as auxiliary sources in pulse designs and as the main source of high pulse energies is rather interesting. The most enticing is the idea of the complete conversion of the energy of flywheel masses into electromagnetic during half of the revolution of a rotor.

The investigation of the operation of the induction pulse-excited generator on an inductive load, taking into account the complete conversion of the kinetic energy of the rotor, is a complex problem. Conditions of the stable self-excitation of a single-phase induction oscillator are unknown. Therefore, in the study of operating modes of these machines, it follows to pay special attention to the determination of the region of their stable self-excitation.

The common method of determining the self-excitation limits lies in the investigation of roots of the characteristic equation, which corresponds to the system of linear differential equations of the voltage of the whole machine. Taking into account the generally accepted assumptions, the system of equations of the single-phase induction machine, in the presence of a capitance in the circuit of the stator, can be presented in the form [3] of:

$$\begin{aligned} &(p^2 x_d + p z_s + x_c) i_\alpha + p^2 x_{ad} i_{\alpha 2} = 0 \ , \\ &p x_{ad} i_\alpha + (p x_2 + z_2) i_{\alpha 2} + (1+s) x_2 i_{\beta 2} = 0 \ , \\ &(1+s) x_{ad} i_\alpha + (1+s) x_2 i_{\alpha 2} - (p x_2 + z_2) i_{\beta 2} = 0 \ , \end{aligned} \quad (1)$$

where $z_s, x_d; z_2, x_2$ are the active and inductive resistances of the stator and rotor; $x_{ad}$ - inductive resistance of the interinduction with coincidence of the axes of windings of similar phases of the stator and rotor; $i_\alpha, i_{\alpha 2}, i_{\beta 2}$ - currents of the stator and rotor in axes $\alpha$, $\beta$ ; s - slip; p - operator.

The characteristic equation of system (1) has the form:

$$a_0 p^4 + a_1 p^3 + a_2 p^2 + a_3 p + a_4 = 0 \ , \quad (2)$$

where

$$\begin{aligned} &a_0 = T_2^2 x'_d \ , \\ &a_1 = T_2 [T_2 z_s + (x_d + x'_d)] \ , \\ &a_2 = x_d + 2 T_2 z_s + T_2^2 x_c + (1+s)^2 T_2^2 x'_d \ , \\ &a_3 = z_s + 2 T_2 x_c + (1+s)^2 T_2^2 z_s \ , \\ &a_4 = x_c [1 + (1+s)^2 T_2^2] \ , \\ &T_2 = \frac{x_2}{z_2} \ . \end{aligned}$$

For determining the conditions in which all the roots of the characteristic equation (or real parts of the combined roots) are positive, we can use the Hurwitz criterion.

An analysis of the Hurwitz determinants shows that the self-excitation of the machine is provided at such ratios of the parameters for which the following inequality is fulfilled:

$$\frac{x_d + x'_d}{2} > x_c > 0 \qquad (3)$$

The most complete analysis of the self-excitation of the induction machines was obtained by solving the equation (2) on a digital computer. As the studies showed, the zone of self-excitation actually lies within $0{,}5(x_d + x'_d) > x_c > 0$, but its dependence on parameters of the machines is rather unique. Plotted on Fig. 1 are boundaries of the zone of self-excitation of the machine, which have different parameters of the rotor windings, in the plane of coordinates $x_c$ and $r_s$. From the curves it follows that the region of self-excitation with a change in parameters of the rotor in the interval $T_2 = \omega(0{,}1 \div 100)$ e·s is changed insignificantly. But with an increase in the resistance of the rotor windings, the boundary is changed, and at $T_2 = \omega 0{,}001$ e·s it is degenerated into the point region at the origin of the coordinates. For checking the obtained solutions, we conducted experimental studies on determining the zone of stable self-excitation, the results of which are presented on Fig. 2.

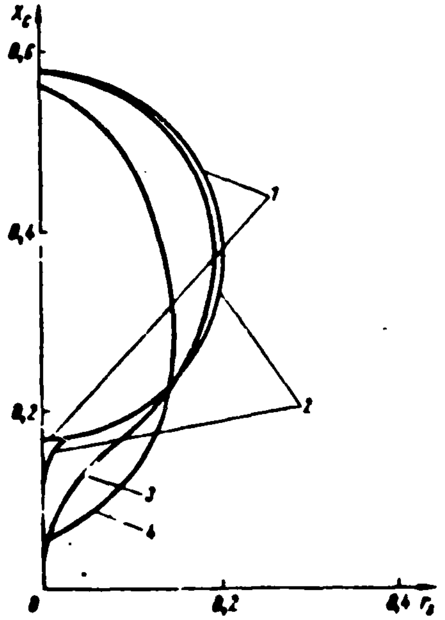


Fig. 1. Regions of self-excitation plotted according to the characteristic equation (2) for a machine having the following parameters: 1 - $T_2$= (10-100)e·s; 2 - $T_2$= $\omega$1 e.s; 3 - $T_2$= $\omega$0.1 e·s; 4 - $T_2$= $\omega$0.01 e·s.

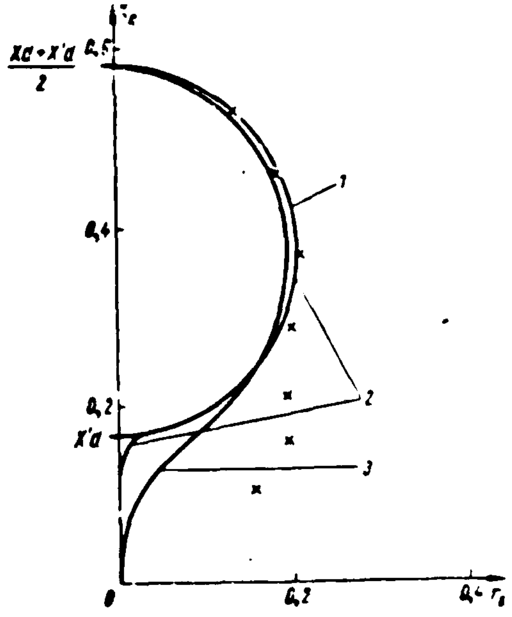


Fig. 2. Comparison of theoretical and determined (experimentally) boundaries of self-excitation and generator with parameters: ($x_d$ = I; $x'_d$ = 0.17; $T_2$ = $\omega$ 0,12 e·s; 1 - ... corresponding ... equation of

Fig. 2 continued: of the circle (4); 2 - $T_2 = \omega 1 e \cdot s$; 3 - $T_2 = \omega 0.1 e \cdot s$; x - experimental points.

From a comparison of the experimental and calculation data for machines with $T_2 = \omega 0.12$ e·s, it is evident that the divergence appears mainly in the region $x_c \approx x'_d$. With an increase in the time constant of the rotor circuits, the lower zone of self-excitation (when $x_c < x'_d$ ) is expanded in defined limits, and the upper zone is narrowed.

Calculations on a computer showed that the boundary of the zone for the single-phase induction machine with a symmetric rotor can be approximately expressed by the equation of the circle

$$\left(x_c - \frac{x_d + 3x'_d}{4}\right)^2 + z_s^2 = \left(\frac{x_d - x'_d}{4}\right)^2 . \quad (4)$$

In general, the magnitude of the capacitance necessary for the self-excitation of the machine must be determined from the relation

$$C > \frac{2}{\omega(x_d + x'_d)} . \quad (5)$$

Thus the studies conducted on the self-excitation of the single-phase induction machine showed the satisfactory convergence of experimental and calculation data; the power of the bank of capacitors for exciting the pulse-excited generator consists of the order of five percent of the pulse-excited power.

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# MECHANICAL FORCES IN ELEMENTS OF THE POWER SUPPLY CIRCUIT OF AN ACCELERATING APPARATUS FROM A PULSE-EXCITED GENERATOR

V.I. Popov, G.A. Sipaylov

Used for creating powerful magnetic fields are different electrophysical devices the windings of which are flowed around by pulsed currents with an amplitude of hundreds of kiloamperes. During the operation, the current-conducting parts of such devices undergo enormous mechanical stresses, which limit the magnitude of the current being passed. The deformations appearing in the windings under the effect of electrodynamic forces (edf) in the powerful magnetic field can become irreversible, and the apparatus is destroyed. In order to design such a device correctly, it is necessary to know the magnitude and distribution of the mechanical stresses in its windings. The ability to determine correctly the stresses by calculation means makes it possible to create a reliable securing of the current-carrying parts, which is capable of withstanding destruction or noticeable deformation.

The volumetric density of the mechanical force acting on the conductor with a current introduced into the magnetic field equals:

$$F = \frac{1}{10}[jH] \; .$$

Consequently, for the calculation of the edf, it is necessary to know the magnetic field strength and distribution of the current density. The main difficulties are associated with the determination of the magnetic field strength H. These difficulties depend mainly on the complexity of the spatial configuration of the current-carrying part of the device. They are increased even more with calculation of the effect of the circular ferromagnetic surfaces.

Usually, in calculations of edf, for simplifying the problem, a number of assumptions is made. In particular, separate sections of the conductors of complex spatial configuration are taken as plane [5, 6]. If this assumption is acceptable at the small curvature of the conductors, or when the winding covers not more than 60°, then in windings which possess great curvature and cover angles up to 180°, for example, any parts of the concentric winding of the stator of a two-pole pulse-excited generator, such an assumption introduces a considerable error.

Secondly, in calculations of edf, the effect of finite dimensions of the cross section of the conductors is usually not considered, i.e., it is considered that the currents flow along the line conductors.

In order to obtain a sufficiently accurate representation about the distribution of mechanical stresses in conductors of complex configuration, what are the windings of the pulse-excited generators, reactors, solenoids, magnets of accelerators, and so on, it is necessary to consider the curvature and finite dimensions of the cross section of the conductors in determining the edf.

In calculations of mechanical stresses in the conductors, determined, as a rule, are values of the axial $F_a$ and radial $F_p$ forces, which for conductors of infinitely small cross section can be expressed by the following [2]:

$$F_{oa} = 10^{-7} i^2 C_a \quad (H) \tag{1}$$

$$F_{op} = 10^{-7} i^2 C_p \quad (H) \quad , \tag{2}$$

where $C_a$ is the axial geometric coefficient; $C_p$ - the radial geometric coefficient; $i$ - current in the conductors.

Coefficients $C_a$ and $C_p$ consider the effect of the spatial position of the conductors on the magnitude of the edf. For conductors at a distance of h from each other and curved along radius R, coefficients $C_a$ and $C_p$ are equal to

$$C_a = \frac{h}{\sqrt{4R^2+h^2}}\left[\frac{2R^2+h^2}{h^2}\left\{E_{(k)} - E_{(\frac{\pi}{2}-\frac{\beta}{4},k)} + \frac{k^2 \sin\frac{\beta}{2}}{2\sqrt{1-k^2\cos^2\frac{\beta}{4}}}\right\} + F_{(\frac{\pi}{2}-\frac{\beta}{4},k)} - K_{(k)}\right](\varphi \cdot \sin\varphi),$$

$$C_p = \frac{R}{\sqrt{4R^2+h^2}}\left[K_{(k)} - E_{(k)} + E_{(\frac{\pi}{2}-\frac{\beta}{4},k)} - F_{(\frac{\pi}{2}-\frac{\beta}{4},k)} - \frac{k^2 \sin\frac{\beta}{2}}{2\sqrt{1-k^2\cos^2\frac{\beta}{4}}}\right]\left(\varphi - \frac{\varphi^3}{12\pi^2}\right),$$

where $\beta$ and $\varphi$ are the central angles which encompass the first and second conductors, respectively; $K_{(k)}$, $E_{(k)}$ - complete elliptical integrals of the first and second kinds, respectively; $F(\frac{\pi}{2}-\frac{\beta}{4},k)$, $E(\frac{\pi}{2}-\frac{\beta}{4},k)$ - incomplete elliptical integrals of the first and second kinds, respectively; $k^2=\frac{4R^2}{4R^2+h^2}$ - the modulus of the elliptical integrals.

As the investigations showed, the calculation according to formulas (1) and (2) for conductors of an infinite cross section gives a considerable error, for the compensation of which it follows to introduce into the calculation formulas the correction coefficient , wheih consider the cross section of the conductors and distance between their axes.

This coefficient can be determined by comparing the forces per unit length of conductors of infinitely small cross section and conductors of finite cross section calculated on the basis of the theorem on the proportionality of the edf to the change in energy of the magnetic field along the coordinate, in the direction of which the force is determined. For busbars of rectangular cross section, the expression for the coefficient of shape and proximity of the cross sections has the form:

$$k_{\varphi}=h\left\{\frac{h-a}{a^2}\ln\left(1-\frac{a}{h+b}\right)+\frac{h+a}{a^2}\ln\left(1+\frac{a}{h+b}\right)+\frac{b^2}{(h+b)[(h+b)^2-a^2]}\right. , \quad (3)$$

where h is the distance between centers of the cross sections; a - width of the busbar; b - height of the busbar.

In order to calculate the effective force acting on the conductor of finite cross section, it is necessary to multiply the edf obtained for conductors of an infinitely small cross section by the coefficient k . Taking the stated above into account, the formulas (1) and (2) for conductors of rectangular cross section are written the form

$$F_a = 10^{-7} i^2 C_a k_{\varphi} \ (N), \quad (4)$$

$$F_p = 10^{-7} i^2 C_p k_{\varphi} \ (N). \quad (5)$$

The The table gives values of coefficient $k_{\varphi}$ calculated from formula (3) for different ratios $\frac{b}{a}$ and $\frac{h}{a}$. Ratios $\frac{b}{a}$ and $\frac{h}{a}$ are determined by construction of the conductors and can be varied in the most diverse manner.

Table

| $\frac{b}{a}$ | $\frac{h}{a}=1$ | $\frac{h}{a}=2$ | $\frac{h}{a}=3$ | $\frac{h}{a}=4$ | $\frac{h}{a}=10$ |
|---|---|---|---|---|---|
| 0,5 | 1,16 | 1,04 | 1,02 | 1,01 | 1,00 |
| 1 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 |
| 2 | 0,74 | 0,90 | 0,95 | 0,97 | 0,993 |
| 3 | 0,60 | 0,80 | 0,88 | 0,95 | 0,987 |
| 4 | 0,50 | 0,71 | 0,82 | 0,91 | 0,981 |

From the table it is evident that for the relatively small changes in ratios b/a and h/a, the coefficient $k_\varphi$ varies in considerable limits. If at calculations of edf the proximity coefficient of cross sections is not considered, at ratios of b/a>1 the result will be excessive, and at b/a<1 it will be understated.

For an estimate of the longitudinal finite cross section of the conductors on the magnitude of the edf, experiments on models according to the method discussed in work [3] were conducted. The models were designed so that the distance h between axes of the busbars rigidly attached to supports could be changed. As a result of the experiments, dependences of $k_\varphi = f\left(\frac{h}{a}\right)$ when $\frac{b}{a} = \text{const.}$ were taken. On Fig. 1 the experimental values of $k_\varphi$ when b/a=2.6 are applied by points. Given there for a comparison is the curve of $k_\varphi$ calculated according to formula (3) with the same ratio b/a.

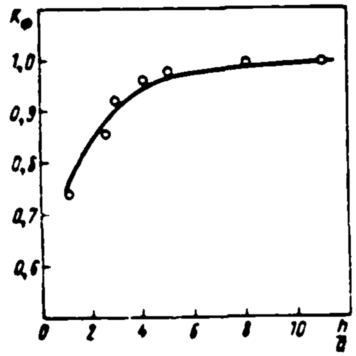


Fig. 1. Dependence of $k_\varphi = f\left(\frac{h}{a}\right)$ when b/a=2.6; ______ - calculation curve.

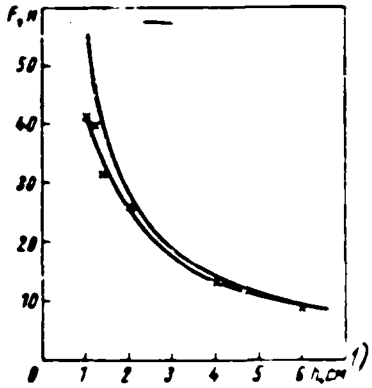


Fig. 2. Curves of forces for b/a=2.6 and current of 3 kA. Key: 1) cm.

Figure 2 gives curves of forces plotted from results of the claculation carried out both without taking into account (curve 1) and taking into account the coefficient of proximity (curve 2) for ratio b/a=2.6 and current of 3 kA. Here the x's denote the experimental values of forces for the same values of b/a and current. From Fig. 2 it follows that the calculation taking the coefficient of shape and proximity of the cross sections into account gives values of forces which agree well with the experimental data. Let us note that with an increase distance h, ther curves are merged. This is explained by the fact that the coefficient $k_{э\varphi}$ tends to unity with an increase in h at a constancy of b/a. Therefore, in those cases when dimensions of the cross section of conductors, at least, are four to five times less than the distance between them, the calculation of the forces can be made according to formulas (1) and (2), assuming that $k_{\varphi}=1$.

The obtained expressions make it possible to determine the electrodynamic forces with sufficient accuracy for conductors with the assigned curvature and cross section. The examined procedure is applicable for the calculation of the edf between the curvilinear conducting parts of different devices in those cases when the effect of the ferromagnetic masses is insignificant.

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