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OPTIMUM SWITCHING OF LOW-VOLTAGE POWER GENERATING
ELEMENTS WITH A NONLINEAR VOLT-
AMPERE CHARACTERISTIC

by

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Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
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Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
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Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
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И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
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К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
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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

* <u>ye</u> initially, after vowels, and after ъ, ь; <u>e</u> elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

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G. A. Baryshnikov, G. P. Levshin and
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(Moscow)

This article examines the question of the optimum switching of a large number of low-voltage power generating elements with nonlinear volt-ampere characteristics and the leakage currents in the system of an increased-voltage current source.

The optimum circuit for connecting power generating elements ensuring with a minimal number of elements assigned voltage and power is found on the basis of the solution to the appropriate variation problem. It is shown that in the optimum circuit diagram every element of the source should work at the maximum power rating; in this case the power being generated by the source is less than the maximum power which the source could generate under lower voltage on the load. Questions of the construction of the resulting volt-ampere characteristic of source with nonlinear power generating elements are considered. Illus. 4. Bibl. 2. pp. 150-154.

Work [1] examines the optimum circuit for switching of power generating elements (EGE) with a linear volt-ampere characteristic (VAC) and current leakages in the system of a source of current of increased voltage, in which the assigned output parameters of source - electrical power $W_{н.и}$ and voltage $V_{н.и}$ - were ensured with a minimum number of EGE. Below we examine the problem of the optimum (ensuring the minimal quantity of EGE at assigned W and V) switching of EGE with nonlinear VAC and leakage currents, since experiments show [2] that real VAC of EGE of some types of the energy converters (field-effect converters, photobattery) can be linearized only in a fairly narrow area, and not over the entire operating range.

The appropriate variation problem, examined in [1], allows generalization to the case of EGE with arbitrary VAC. As also in [1], we substitute a current source composed of l series-connected units, each of which consists of z parallel-connected EGE of the same type with nonlinear VAC (Fig. 1) and with leakage resistance R_y, continuous power generating zone (EGZ) 1234, and zone 1465 which characterizes the presence of "leakage currents" (Fig. 2).

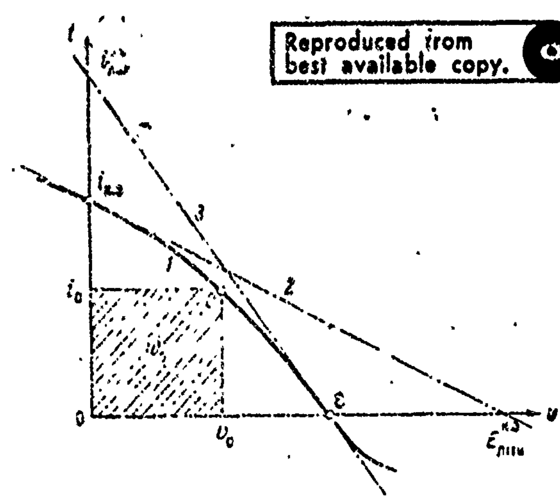

Fig. 1. The volt-ampere characteristic of the power generating element (1 - nonlinear characteristic; 2 - the linearization of characteristic in the neighborhood of the point of short circuiting; 3 - the linearization of the characteristic in the neighborhood of the no-load point.

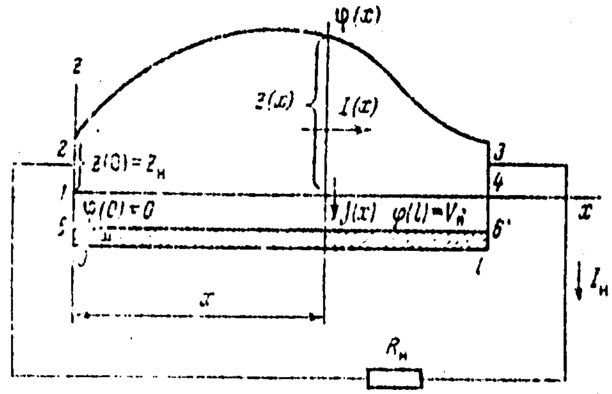

Fig. 2. Equivalent power generating zone. Integral values of x correspond to the reference number of a series-connected unit; ш - bus (conducting housing of the source).

In this case equations (3)-(6) in work [1], which describe the distribution of currents and potentials to EGZ, retain their form if the expression for the voltage being developed by the EGZ with linear VAC,

$$v_{экв} = E(1 - iR / E), \quad (1)$$

is replaced by v(i), where v(i) - arbitrary nonlinear function of the value of the current through one element i = I/z; I - the instantaneous value of current through the EGZ.

Finding the optimum circuit diagram is equivalent to the solution of the following variation problem: find the minimum of functional $\int_0^l z(x)dx$ when nonholonomic connections exist; for a source with an ungrounded load in the selected system of coordinates the connections are written in the form

$$\begin{aligned} \varphi' - v(i) &= 0, \\ I' + J &= 0, \end{aligned} \quad (2)$$

and the boundary conditions

$$I(0) = I(l) = I_{н.н}, \quad \varphi(l) = \varphi_{н.н}.$$

Here $I_{н.и}$ - current in the load in the calculated regime (at assigned $W_{н.и}$ and $V_{н.и}$: $I_{н.и} = W_{н.и}/V_{н.и}$).

The solution of this problem is conducted just as in work [1] for the case of EGE with linear VAC. The system of Euler equations thus obtained, with the appropriate nonholonomic connections and boundary conditions, makes it possible to obtain the following relationship:

$$v'(i)i + v(i) = [v(i)i]' = (w)' = 0,$$

where w - the power of EGE at an arbitrary point of the VAC.

The integration of this relationship gives

$$iv(i) = w_0, \qquad (3)$$

where w_0 - the maximum power of EGE achievable when $i = i_0$, $v(i_0) = v_0$ (Fig. 1). Equality (3) yields the conclusion that at optimum switching of current sources with nonlinear VAC it is necessary that each EGE operate in its optimum regime. The distribution of EGE in the units [$z = z(x)$], which ensures the minimum number of elements N with the assigned parameters (operation of the source at the calculated point) and the distribution of full current over the source takes the form

$$z = z_н \exp\left\{-\frac{v_0}{2R_y i_0}\left[\left(x - \frac{l}{2}\right)^2 - \left(\frac{l}{2}\right)^2\right]\right\}, \qquad (4)$$

$$I = I_{н.н} \exp\left\{-\frac{v_0}{2R_y i_0}\left[\left(x - \frac{l}{2}\right)^2 - \left(\frac{l}{2}\right)^2\right]\right\}, \qquad (5)$$

where $z_н = I_{н.н}/i_0$ - the initial number of EGE in the unit.

In the overwhelming majority of the cases it is not sufficient to know the parameters of the source only in the optimum regime; it is necessary to have available the entire volt-ampere characteristic of the source, i.e., the dependence

$$\varphi(l) - \varphi(0) = V_н = V_н(I_н).$$

To get this dependence it is necessary to integrate the first equation of system (2), which requires that we first find the function

$$i(x, I_н) = I(x, I_н) / z(x).$$

From the same system we can obtain

$$\left(\frac{I'}{z}\right)' + v\left(\frac{I}{z}\right) / R_y = 0, \qquad (6)$$

since

$$\varphi - \varphi_0 = I R_y / z.$$

Substitution of expression (4) into equation (6) reduces it to a differential second order equation relative to I; in the general case it is nonlinear, owing to the nonlinearity of the initial volt-ampere characteristic of the EGE, i.e., of the function $v(I/z) \equiv v(i)$. In the general case the integration of this equation in explicit form is impossible.

In the particular case for linear VAC, i.e., when i and v are connected by correlation (1), equation (6) is reduced to the comparatively simple form

$$I'' + k^2\left(x - \frac{l}{2}\right)I' - k^2 I + \frac{E}{R_y} z_н \exp\left\{-\frac{k^2}{2}\left[\left(x - \frac{l}{2}\right)^2 - \left(\frac{l}{2}\right)^2\right]\right\} = 0. \quad (8)$$

Here E - the electromotive force of EGE with linear VAC; R - the internal resistance of EGE with linear VAC; $k^2 = R/R_y$.

Solution of equation (8) with boundary conditions in the case of an ungrounded load

$$I(0) = I(l) = I_н,$$

where I_H - the variable value of the current through the load, takes the form

$$I = \left(I_н - \frac{Ez_н}{2R}\right)\frac{\exp\left[-k^2(x - l/2)^2/2\right] + \sqrt{\pi/2}\,k(x - l/2)\Phi[k(x - l/2)]}{\exp\left[-k^2l^2/8\right] + \sqrt{\pi/2}\,(kl/2)\Phi(kl/2)} +$$

$$+ \frac{Ez_н}{2R}\exp\left\{-\frac{k^2}{2}\left[\left(x - \frac{l}{2}\right)^2 - \left(\frac{l}{2}\right)^2\right]\right\}. \quad (9)$$

The resulting VAC of a current source composed of EGE with linear VAC and leakage currents at optimum commutation, obtained as the result of integration of (2), takes the form

$$V_н = 1/2\,El(1 + z) - I_н Rlz/z_н. \quad (10)$$

where

$$\varkappa = \frac{\sqrt{2\pi}\,\Phi(kl/2)}{kl\,[\exp(-k^2l^2/8) + \sqrt{\pi/2}\,kl\Phi(kl/2)/2]} \leq 1$$

- for an ungrounded load and

$$\varkappa = \frac{\sqrt{2\pi}\,\Phi(kl)}{2kl\,[\exp(-k^2l^2/8) + \sqrt{\pi/2}\,kl\Phi(kl)]} \leq 1$$

- for a grounded load,

$\Phi(y) = \frac{2}{\sqrt{2\pi}} \int_0^y \exp\left(-\frac{t^2}{2}\right) dt$ - the integral of probability. As follows from the actual statement and solution of the variation problem, for a current source with optimally switched EGE (linear and nonlinear) the utilization factor of a source with voltage k_V, which can be defined as the ratio of the voltage being developed by source at calculated point $V_{Н.И}$ to the sum of the voltages being developed by each consecutively connected unit operating at the optimum point, is equal to 1, i.e.

$$k_V = V_{н.и} / v_0 l = 1.$$

The utilization factor of a source with power k_W is defined as the ratio of the power of the source at the calculated point of $W_{Н.И}$ to the sum of the maximum capacities of the EGE included in the source, i.e.,

$$k_W = W_{н.и} / w_0 N.$$

Correlation (10) is conveniently presented in the form

$$V_H = E_H - I_H R_H.$$

where $E_H = El(1 + \varkappa)/2$ - is the emf of the source, $R_H = Rl\varkappa/z_H$ - the internal resistance of the source.

From this expression it is evident that as a result of the leakage currents the emf of a source with linear EGE differs from the sum of the emf of the series-connected units. This distinction can be taken into account by the utilization factor of the source with respect to the emf k_E. It is evident that

$$k_E = E_H / El = (1 + \varkappa)/2.$$

It is convenient to present the internal resistance in the form $R_H = Rlk_R/z_H$. From correlation (10) it follows that $k_R = \varkappa$.

It is interesting to note that for the current source which has an optimum wiring diagram for EGE with linear VAC the voltage at the operating point is $V_{H.H} > E_H/2$. Thus, because of the linearity of the resulting VAC (equation (10)) the obtained EGZ can yield high electrical power, but at a voltage which is less than the assigned $(V_{H.H})$.

It is evident that EGE of arbitrary configuration assembled from EGE with linear VAC will have linear resulting VAC (this follows from the linearity of the problem). The zone for which the assigned current and voltage correspond to the point of maximum power on its resulting VAC will have a large "length" l_2 and small value of z_{H_2} (Fig. 3). However, in this case $N_2 > N_1$

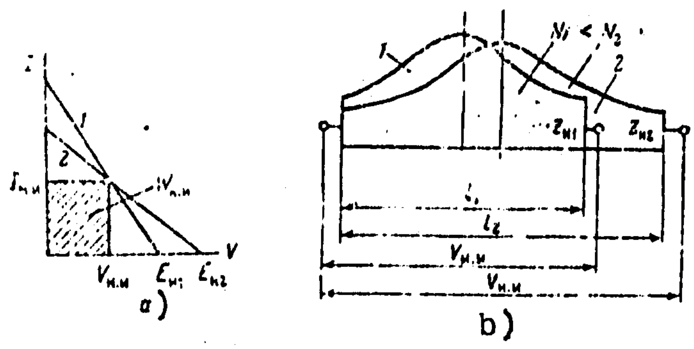

Fig. 3. Resultant volt-ampere characteristic of source a) and the distribution of the elements in the source b): 1 - optimum switching; 2 - switching at which $V_{Н.Н} = E_И/2$.

and consequently $k_{N_1} < k_{N_2}$. The displacement of the operating point into the sphere of increased voltages is caused by the nature of the distribution of potential over the "length" of the EGE in different operating conditions. For sources whose EGE have a linear VAC it follows from the first equation of system (2) and from equation (9) that

$$\varphi(x) = xE/2 + \frac{\left[\frac{E}{2R} z_н - I_н\right] P \sqrt{\frac{\pi}{2}} \exp\left(\frac{k^2 l^2}{8}\right) \exp\left(-\frac{k^2 x^2}{8}\right)\left\{\Phi\left[k\left(x - \frac{l}{2}\right)\right] + \Phi\left(\frac{kl}{2}\right)\right\}}{z_н k \left[1 + \sqrt{\frac{\pi}{2}} \frac{kl}{2} \Phi\left(\frac{kl}{2}\right) \exp\left(\frac{k^2 l^2}{8}\right)\right]}.$$

The corresponding graphs of the change in ϕ in short-circuit (C), calculated (B) and no-load (A) conditions are given on Fig. 4. It is evident that in short-circuit conditions at the ends of the EGZ $d\phi/dx < 0$, i.e., the end elements operate in as energy consumers (the voltage developed in the middle part of the EGZ, where $d\phi/dx > 0$, is applied to them). Then the current through the end elements will be greater than $i_{К.З}$, and the

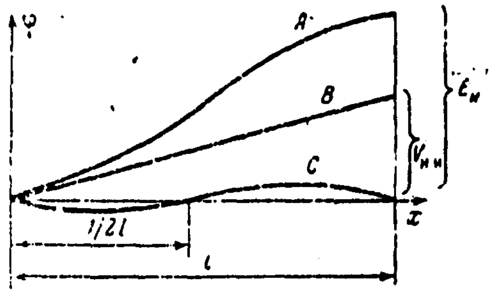

Fig. 4. The distribution of potential in the source with switching (A - no-load regime, B - optimum operating conditions, C - short-circuit conditions).

short-circuit current of the EGZ will be greater than $i_{к.з}z_{н}$. Thus the resulting VAC are, as it were, turned clockwise at certain angle around the calculated point. The emf of the resulting VAC is correspondingly reduced.

Everything said relative to the displacement of the calculated point from the point of the maximum power of the EGZ can be generalized to the case of a source with nonlinear EGE.

For a current source for which EGE connection is optimum and VAC is nonlinear, expressions for calculation of the number of elements N and the utilization factor of the source in terms of power k_W can be taken from Table 1 in work[1] [1] with replacement of the quantity in the appropriate expressions by the quantity v_0/i_0R_y.

In principle the resulting VAC of the source with nonlinear EGE can be constructed only after solution of equation (6). In the general case its integration in quadratures is impossible; in connection with this we are limited to finding the three base points of the resulting VAC in the nonlinear case, including the already known calculated point. By conducting linearization near points $i_{к.з}$ and ε (Fig. 1), it is possible to use known expressions

[1]By oversight of the authors, in Table 1 of work [1] in the first and second lines of the third and fourth columns the coefficients k_E and k_R in front of E and R were omitted.

(see [1])for the linear case and to find $I_{к.з}$ and $E_{и}$. Naturally, this approach will be valid if the operating conditions of each EGE differ little from the short circuit and no-load conditions, respectively. This requires that the following criteria be fulfilled (Fig. 1):

short circuit conditions – $\max|dI/dz - I_{к.з}| \leqslant \varepsilon I_{к.з}$;

no-load conditions – $\max|d\varphi/dz - \varepsilon| \leqslant \varepsilon$.

The use of the formulas obtained above permits reducing these criteria to the form:

short circuit conditions – $k_{к.з} l \leqslant 0{,}8 - 1,\ k_{к.з} = E^{опт}_{к.з}/R_1 i_{к.з}$;

no-load conditions – $k_{х.х} l \leqslant 0{,}8 - 1,\ k_{х.х} = [illegible] / R_y i^{опт}_{х.х}$.

Conclusions. 1. In the optimum circuit for switching EGE with nonlinear VAC and leakage currents every element in the system of the current source should operate in maximum-power conditions.

2. The power of the current source at the calculated point with optimum switching of the EGE is less than the maximum power of this source which can be obtained under voltage on the load which is less than the calculated.

3. In a number of cases it is possible to use the relationships obtained for EGE with linear VAC for construction of three characteristic points of the resulting VAC of the source, with appropriate linearization of the VAC of the EGE in these characteristic points.

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