CASCADE MAGNETOCUMULATIVE GENERATOR WITH FLUX INTERCEPTION

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Experiments on the development of a sectioned, spiral, magnetocumulative generator, whose initial sections are employed for trapping and forcing out magnetic flux, while the last section is used as a load, are described. The load is constructed in such a way that it can be inductively coupled with the first section of the same generator, thereby forming a multicascade system realizing interception and compression of the flux on transition from one cascade into the next cascade. The electrical characteristics, losses, and functional limitations of such a system are determined.

1. General Principles. Schematic Diagram of the Generator and Possible Applications of the Generator. A magnetocumulative (MC) generator is a unique source of high pulsed power, which transforms an appreciable fraction of the energy stored in the charge of a chemical explosive into an electromagnetic energy pulse. Thirty years have elapsed since the principle of magnetic compression was formulated. During this period primarily Soviet and American researchers have developed tens of variants of different MC generators, and record high current strengths, magnetic field strengths, energy levels, and pulsed power levels, previously considered to be fantastic, have been achieved [1-3]. At the same time very high (tens of percent) efficiencies of conversion of the energy stored in the explosive into electromagnetic energy have been achieved, and an explosive source at high energy levels that can compete commercially with all present sources of other types has been developed [4].

This work is concerned with the possibilities of employing the principles of magnetic cumulation for the development and creation of sources for powering powerful explosive generators. The current status of this problem is paradoxical and abnormal: in generating from an explosive charge tens of megajoules of energy, it is necessary to create an initial store of electromagnetic energy in the MC generator primarily by charging cumbersome and quite expensive and archaic capacitor banks.

We shall formulate the requirements that the power source must meet. First, it must operate from a source with a stored energy of $\sim$100 J and provide in a quite large inductive load ($\sim$10 μH and higher) an energy of $\sim$100 kJ. Second, while such a source must be relatively simple, cheap, and reliable, it must also be possible to change the output parameters in order to ensure matching with a wide range of different powerful MC systems. We call attention to the fact that the energy output of this generator (100 kJ) corresponds to only 20 g of explosive or, with an energy conversion efficiency of only 1%, a charge of 2 kg, a magnitude which is negligible compared with the hundreds of kilograms employed in powerful modern MC generators [4]. For this reason it is pointless to strive to achieve high conversion efficiency in the power source.

It is hardly possible or desirable to meet the enumerated requirements by developing a small classical MC generator loaded directly on a small inductance, since for high energy gains the initial inductance of such a generator would take on enormous values, and the experimentally observed growth of the flux losses as the coefficient of restructuring of the inductance in the circuit increases would unavoidably destroy the best design of this type.

Among the possible solutions of this problem the most attractive is to construct a multicascade generator with flux interception. The principle of flux interception, formulated by Chernyshev [5] and Pavlovskii [6], is not yet widely recognized, though the results published by the authors are very interesting and promising. In the cascade variant this principle leads to compensation of flux losses in the preceding cascade by

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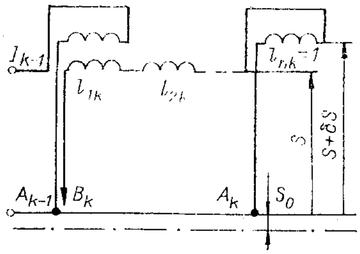

Fig. 1

capture of flux in the large inductance of the next cascade, and the operation of the generator can even be accompanied by an increase in flux toward the end, which cannot be achieved in other types of MC generators.

The schematic diagram of the generator of interest is shown in Fig. 1, which shows in detail the k-th cascade of the generator, which consists of n sections with inductances ℓ_{1k}, ℓ_{2k}, ..., ℓ_{nk}. All inductances are referred to the inductance of the last section, so that it is assumed that $\ell_{nk} = 1$. Through its first inductance ℓ_{1k} the k-th cascade is coupled inductively to the last inductance of the preceding cascade, which we shall assume is the same as the last inductance of the k-th cascade. The ends of the last section of all cascades are closed on a continuous conductor $\ldots A_{k-1}A_k \ldots$, the beginning of the first section of each cascade B_k forms an isolated break, which is closed with the motion of the conductor $\ldots A_{k-1}A_k \ldots$, driven by the explosive charge located inside it. Prior to the closure of this break the flux in the individual cascade is compressed. After closure the interception of flux is completed and its compression begins in the next cascade, which repeats the preceding stage, if the cascades are identical. The total inductance of the k-th cascade, normalized to the inductance of its last section, is the so-called restructuring factor of the MC circuit λ_k, which for an ideal lossless generator is equal to the current gain i and the increase in the energy ε, i.e.,

$$\lambda_k = \sum_1^n l_{ik},\quad i_k = \lambda_k,\quad \varepsilon_k = \lambda_k,\quad \varphi_k = 1.$$

Change in Flux and Energy Gain Accompanying the Triggering of One Cascade. A cascade generator with flux interception has a number of specific characteristics, which distinguish its operation from that of a classical MC generator. We shall examine them.

Assume that at the beginning of the operation of the k-th cascade a flux φ_k^0 is trapped in it. This means that a magnetic energy

$$\varepsilon_k^0 = (\varphi_k^0)^2/2\lambda_k \tag{1.1}$$

is initially stored in the cascade. As a result of a reduction of the inductance by a factor of λ_k the current in the last section of the cascade is i_k times higher than the starting value. At the same time the flux in the last section of the cascade under study is $\varphi_k = \varphi_k^0 i_k/\lambda_k$. If the coefficient of coupling of the last section of the k-th cascade with the first section of the next cascade is denoted by ϰ, then the flux

$$\varphi_{k+1}^0 = \varkappa\varphi_k \sqrt{l_{1k+1}} = \varkappa\,(i_k/\lambda_k)\,\varphi_k^0 \sqrt{l_{1k+1}} \tag{1.2}$$

penetrates the inductance created by the first section of the (k + 1)-st cascade. It is precisely this flux that is intercepted in the (k + 1)-st cascade and subjected to further compression. Before compression starts, however, because of interception there occurs an undesirable, but unavoidable, phenomenon: there arises in the circuit of the (k + 1)-st cascade a current which maintains the trapped flux φ^0_{k+1} which is redistributed from the inductance ℓ_{1k+1} into the large inductance λ_{k+1}. This process is accompanied by definite losses of energy, which by the onset of compression in the (k + 1)-st cascade equals

$$\varepsilon_{k+1}^0 = (\varphi_{k+1}^0)^2/2\lambda_{k+1}. \tag{1.3}$$

It is easy to see from (1.1)-(1.3) that with the triggering of the k-th cascade there occurs an increase in energy

$$\varepsilon_k = \varepsilon^0_{k+1}/\varepsilon^0_k = \varkappa^2 l_{1k+1}(i_k)^2/\lambda_k\lambda_{k+1} \tag{1.4}$$

and flux

$$\psi_k = \varphi^0_{k+1}/\varphi^0_k = \varkappa i_k \sqrt{l_{1k+1}}/\lambda_k. \tag{1.5}$$

The significant quantity in these formulas is the ratio i_k/λ_k, which represents the remnants of the flux remaining up to the end of the operation in the k-th cascade. Experiment shows that for $\lambda_k \sim 100$ in the best generators $i_k/\lambda_k \sim 0.2$-0.4 and decreases as λ increases [1-3]. Therefore in order to obtain a good increase in energy ε and flux gain ψ moderate values of λ and as large values of κ as possible must be used. Based on technological considerations for production of this generator it should be assembled using identical cascades, allowing the possibility of placing the spiral of the first section of the last cascade into the last section of the preceding cascade. Sectioning for the purpose of optimizing the generator and reducing losses in it must be performed by splitting the loops on transition from one section to the next section [1].

We shall examine several variants of the cascade with splitting of the loop into two loops. With one splitting $n = 2$, $\ell_1 = 4$, $\ell_2 = 1$, $\lambda = 5$. For $\varkappa = 0.9$ and no losses ($i/\lambda = 1$) calculations using the formulas (1.4) and (1.5) give $\psi = 1.8$ and $\varepsilon = 3.24$, which is not very high. By reducing the flux loss factor i/λ to 0.6, we obtain $\psi = 1.08$ and $\varepsilon = 1.166$. For two splittings $n = 3$, $\ell_1 = 16$, $\ell_2 = 4$, $\ell_3 = 1$, $\lambda = 21$. For $\varkappa = 0.9$, $i/\lambda = 1$ the flux and energy gains equal $\psi = 3.6$, $\varepsilon = 12.96$ and even a reduction of $1/\lambda$ to 0.6 leaves good gains ($\psi = 2.16$; $\varepsilon = 4.67$).

A third splitting gives $n = 4$, $\ell_1 = 64$, $\ell_2 = 16$, $\ell_3 = 4$, $\ell_4 = 1$, $\lambda = 85$ – the restructuring of the circuit is too large in order to hope for a good value of the indicator of flux conservation in the cascade i/λ. Further increase in the number of sections is hardly desirable owing to the increase in the flux losses in the cascade. Splitting into more than two loops improves the spatial geometry of the field and probably has a positive effect for reducing the flux losses, but leads to sharper jumps in the inductance accompanying the transition from one section to another within the cascade. These two factors have an opposite effect on the quality of the operation of the generator, and the problem arising can be solved only by performing appropriate experiments.

Model of Flux Losses. Flux losses in spiral multiloop generators are usually much larger than the losses in generators with the simplest geometry of the flat busbar type. If the possibility of rough errors in the preparation of the generator, such as misalignment of the axes of the spiral and the moving armature, is eliminated, then there remain flux leakages in the conductor and contact losses. Because the magnetic flux is concentrated in the zone where the armature collides with the spiral the contact losses may be determining. Jet and plasma phenomena in the collision zone also contribute to an increase in the contact losses. Assuming that the contact losses are the main losses, it is possible to relate the flux lost $\Delta\Phi$ with the inductance $\delta L'$ cut off in the contact, writing the equation for the losses in the form

$$\Delta\Phi = -I\delta L'. \tag{1.6}$$

It is obvious that the contact losses occur over a fraction of the area δS, occupied by the loops of the spiral. Using the well-known dependence of the inductance of a solenoid on the linear density of the loops n and the area and taking into account the fact that over the time Δt an inductance with a length of $D\Delta t$ along the generatrix (D is the velocity of the detonation of the explosive charge) is cut off, we obtain

$$\delta L' \sim \delta S n^2 D \Delta t. \tag{1.7}$$

On the other hand, during the operation of the spiral generator the change in its inductance over the time Δt is given by

$$\Delta L \sim -(S - S_0) n^2 D \Delta t. \tag{1.8}$$

Here S is the effective transverse cross section of the spiral; S_0 is the starting section of the armature with the explosive charge. From (1.7) and (1.8), taking into account the sign of the change in the inductance of the generator, we find $\delta L' \sim -\delta S \Delta L/(S - S_0)$ or $\delta L' = -\alpha\Delta L$, where the adjustable parameter α is in any case proportional to the ratio of the area occupied by the loops of the spiral to the cross section of the free space in the generator.

The assumptions adopted permit writing (1.6) in the form of the equation

$$d\Phi = \alpha I dL, \tag{1.9}$$

which can be simply integrated and gives the change in the flux with the operation of the generator

$$\varphi = \Phi/\Phi_0 = (l/\lambda)^{\alpha}$$

and the current gain

$$i = I/I_0 = \Phi L_0/\Phi_0 L = (\lambda/l)^{1-\alpha}. \tag{1.10}$$

Efficient Shaping and Voltages. Since during the operation of the multicascade generator described above the flux must increase and can reach large values toward the end of the operation with a high load inductance, the rate of change of the flux and the concomitant voltages may turn out to be the decisive obstacle for realizing the planned generator. To reduce the danger of electric breakdown an appropriate law for development of the inductance as a function of time $\ell(t)$ must be chosen. Obviously the optimal generator will be one that creates a constant voltage V_0 throughout its entire operating time, guaranteeing the absence of electrical breakdown. This means that the condition $L(t)dI/dt = V_0 = \text{const}$ must hold, and using this condition we obtain from the equation for the electric circuit (1.9)

$$(1-\alpha) I dL/dt = -V_0$$

or, in a dimensionless form, when the inductance is scaled to the inductance of the load L_f, the current is scaled to the starting current I_0, and the time is scaled to the compression time t_1,

$$(1-\alpha) i dl/d\tau = -V_0 t_1/L_f I_0 = -V_0 t_1 \lambda/\Phi_0. \tag{1.11}$$

Substitution of (1.10) into (1.11) gives the equation

$$(1/l^{1-\alpha}) dl/d\tau = -V_0 t_1 \lambda^{\alpha}/\Phi_0(1-\alpha), \tag{1.12}$$

whose solution must immediately satisfy the two conditions:

$$l(0) = \lambda \text{ for } \tau = 0,\ l(1) = 1 \text{ for } \tau = 1. \tag{1.13}$$

From the first condition we obtain (1.12) in the form $\ell = \lambda(1 - V_0 t_1 \alpha\tau/\Phi_0(1-\alpha))^{1/\alpha}$.

The second condition in (1.13) permits determining the law for develoment of the inductance as a function of the parameter α and λ and the time

$$l = \lambda[1 - \tau(1 - 1/\lambda^{\alpha})]^{1/\alpha}$$

and the voltage in the generator $V_0 = (\Phi_0/t_1)(1 - 1/\lambda^{\alpha})(1-\alpha)/\alpha$. In the absence of losses ($\alpha \to 0$) these formulas transform to the well-known power law for development of the inductance

$$l = \lambda^{1-\tau}$$

and

$$V_0 = (\Phi_0/t_1) \ln \lambda. \tag{1.14}$$

We note that sectioning by the method of splitting loops permits satisfying approximately the power law, while the working voltage exceeds the characteristic induction emf Φ_0/t_1 by at least a factor of $\ln \lambda$.

Other Restrictions. Aside from electrical breakdown catastrophic deviations in the operation of the spiral generator can arise because of mechanical movements or distortion of the spiral by large magnetic pressures. To predict such undesirable phenomena it is necessary to increase the mechanical strength of the spiral against both axial and radial stresses. This is usually achieved by using an exterior winding made of fiberglass fabric permeated with epoxy resin. As experiment has shown, the choice of the diameter of the conductors employed for the spiral, the insulation of the conductors, and the special interloop insulation plays an important role.

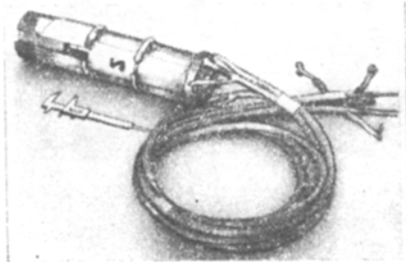

Fig. 2

TABLE 1

Number of experiment	Section number	Number of entries	Number of loops in a section	Total number of loops in the spiral	Section length	Pitch of the loops	Wire diameter	Wire insulation	Distance between turns	Diameter of spiral	Length of spiral	Diameter of inner current conductor	Thickness of the wall of inner current conductor	Breakdown voltage of the insulation, kV
					mm									
1–3	1 2 3	4 8 16	16 8 4	28	86 86 86	4 8 16	1,0 1,0 1,0	0,01 0,01 0,01	0,02	60	258	30	2	Not greater than 5
4–5	1 2 3	3 6 12	16 8 4	28	100 100 100	6 12 24	2,0 2,0 2,0	0,01 0,01 0,01	0,02	67	300	30	2	Not greater than 5
6	1 2 3	4 8 16	20 10 5	35	172 140 132	8,6 13,8 26,6	1,9 1,9 1,9	0,01 0,01 0,01	0,02	60	444	30	2	Not greater than 5
7	1 2 3	2 6 18	16 6 2	24	108 108 108	6,4 18 54	2,0 2,0 2,0	0,2 0,2 0,2	1,0 0,6 0,6	60	324	30	2	Greater than 10
8	1 2 3 4	2 4 8 16	21 10 5 2	38	153 170 170 130	7,0 16 32 60	2,5 2,5 2,5 3,0	0,01 0,01 0,01 0,1	1,0 1,5 1,5 0,2	60	600	30	2	Not greater than 5 5 10

2. Construction of the Generator and Experimental Results. In accordance with the foregoing several different sectioned small spiral generators (one of which is shown in Fig. 2), whose basic structural features are described in Table 1, were built and tested. The tested generators differed by the insulation of the loops, the interloop insulation, the diameter of the wire used to make the spiral, and the number of turns in the sections. The structure was made mechanically strong by winding the spiral with fiberglass cloth permeated with epoxy resin. The experiments performed were also distinguished by the method used to power the generators: in experiments 1-5 the generators were connected directly to a capacitor bank; in experiments 6-8 the generators were powered from a battery consisting of a transformer, simulating transfer and interception of flux from one cascade to another. The purpose of the experiments was to determine the losses and the energy gain in one cascade of the generator.

In the experiments the electrotechnical indicators of the generator were recorded section by section, and the powering parameters and the results of compression were also recorded. Figure 3 shows an oscillogram of flux compression in a three-section generator with squeezing of the magnetic field out of the first two sections into the third section. The top beam recorded the current in the last section of the generator, and the bottom beam recorded the derivative of this current. The oscillogram of the experiment with the four-section generator is shown in Fig. 4, where both beams recorded the current in the last section, but with a gain differing by a factor of ten. The frequency of the time marker in both oscillograms equals 100 kHz.

The experimental results are summarized in Table 2 (the standard notation was employed; the zero index refers to the starting conditions and f refers to the end of the operation of the generator). The experiments 1-3 must be regarded as being unsuccessful, because of the

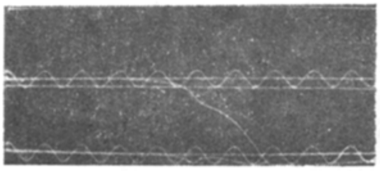

Fig. 3

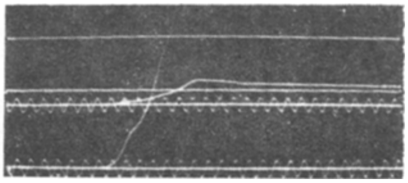

Fig. 4

TABLE 2

No. of experiment	L_0	L_f	I_0	I_f	E_0	E_f	i	ε	Φ_0	Φ_f	φ
	μH		kA		kG				mWb		
1	8,66	0,141	65,0	28	18,3	$55{,}3\cdot 10^{-3}$	1,5	$3\cdot 10^{-3}$	562	4,0	0,007
2	8,55	0,232	65,0	162	18,3	3	2,5	0,16	562	37,0	0,067
3	9,97	0,380	60,0	120	17,9	2,7	2,0	0,15	598	45,0	0,076
4	9,40	0,480	50,0	400	11,7	40,0	8,1	3,42	460	200,0	0,43
5	9,28	0,440	50,0	461	11,6	46,8	9,2	4,03	464	203,0	0,44
6	9,40	0,416		249	1,4	13		9,30	165	103,4	0,63
7	7,42	0,304		396	2,7	23,8		8,82	200	120,4	0,60
8	9,68	0,132		1376	8,7	125		14,36	410	181,6	0,44

excessively high flux losses and the associated loss of the possibility of increasing the electromagnetic energy. Analysis of the details of the experiments and additional control experiments showed that the failure of experiments 1-3 is attributable to the mechanical distortion of a very thin layer of lacquer insulation, coating the loops of the spiral, and the fact that there was no special interloop insulation. More careful permeation with epoxy resin and increasing the diameter of the wire employed for the spiral winding in experiments 5-6 increased the flux conservation factor φ up to 0.44. The introduction of special interloop insulation in experiment 6 raised φ up to the acceptable value of 0.63. Coating of the conductors with an additional, quite strong and thick, insulation ($\sim$0.2 mm) in experiment 7 substantially increased the electrical strength of the generator and had virtually no effect on current conservation and energy gain in the cascade. An attempt to force the cascade by introducing a fourth section and increasing the restructuring factor of the circuit somewhat reduced the flux conservation indicator, but not so much as to reduce the energy gain with an increasing restructuring factor. On the contrary, in this experiment the value of ε reached the highest value achieved.

The experiments had the drawback that the electrical voltage was not measured. We shall estimate it using the formula (1.14), taking into account in it the flux losses by replacing Φ_0 with Φ_f. This estimate gives for experiments 7 and 8 a voltage of not less than 6.4 and 13 kV, respectively.

Transfer to serial connection of the cascades will increase the voltage at the transitions from one cascade to another and will somewhat reduce, because of the nonideality of the transformer link, the energy characteristics and increase the total flux in accordance with the discussion of Sec. 1.

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