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This work describes results of tests on three models of disc generators, two big models of which operated in compressed gas. The highest potential reached by the last model was V_n = 210 kV at idle run. Peak currents and short-circuit currents reached 0.5 - 0.6 mA. At a charging current of 0.2 - 0.3 mA the secondary potential reached 160 - 170 kV.

INTRODUCTION

In a previous work (Models of High-Voltage Generators Operating in a Liquid Dielectric) describing tests on models of electrostatic high-voltage machines, we investigated the operating principle of electrostatic machines developed by us and analyzed their working cycle; namely: 1) charging at primary potential, 2) rising of potential, 3) cut-off of charge at high potential, and 4) lowering of potential of the remaining charge to the primary potential. The dependence of secondary potential on charge current (exterior characteristic) is expressed by the equation:

$$V_2 = V_{max}\left(1 - \frac{I}{I_0}\right) \qquad (1)$$

where I_o is the maximum current (short-circuit current), and V_{max} is the peak potential which can be obtained in a high-voltage circuit if the machine has no leaks. In this case the value of V_{max} is determined by the ratio between maximum capacity C_1 at the start of the charge at the primary potential and minimum capacity C_3 at cut-off of charge in the high-voltage system:

$$V_{max} = \frac{C_1}{C_3} V_1 \qquad (2)$$

Relation (1) is represented by the dotted line in Figure 1.

In reality due to the presence of leaks, the secondary potential V_n is determined by the relation:

$$V_n = I_f R_f \qquad (3)$$

where I_f and R_f are current strength and resistance to leakage respectively.

The exterior characteristic of the machine varies and instead of the characteristic 1 we shall obtain the characteristic represented by the continuous line in Figure 1.

The optimum operating condition of the machine will be at that charge I_m for which potential V_2 approaches V_n and product $I_m V_n$ is maximum. In order to increase the power and efficiency of operation of the machine, capacity C_3 should be kept as low as possible; this produces an increase of the characteristic slope and as a result enables one to obtain a strong current at the same potential V_2. Figure 1 shows as an example two characteristics: capacity C_3 is twice smaller in the second case than in the first. It is possible to verify that by decreasing the capacity C_3 we considerably increase the efficiency of the machine.

At the same time the increase of capacity C_1 (on account of increase of the operating area transporting the charge) produces bigger charging currents.

Hence, in order to increase the power and efficiency of operation of the electrostatic machine, one must try to decrease capacity C_3 and to increase capacity C_1.

One of the possibilities of increasing C_1 and decreasing C_3 (introduction of internal screens) was checked by us in a previous work on a two-rotor model. We expected to obtain a further essential increase of capacity C_1, by enlarging the area of the rotor. Thus we were led to an entirely different construction of the machine; namely, we replaced the cylindrical rotor by round discs.

2. A SMALL 11-DISC MODEL

The basic elements of the model are flat ebonite discs with metallic sectors, insulated from each other. One system of discs I is assembled on the axis and constitutes the rotor; the second system of immobile discs II makes the stator.

Discs I have the shape represented in Figure 2; here 1 - metallic sectors and 2 - ebonite discs. The discs II are schematically represented in Figure 3 (their exterior diameter is somewhat larger than that of discs I); 3-- metallic sectors and 4 - ebonite ring.

Figure 4 represents a vertical cross-section through the model. All sectors of the separate rotor discs lying on one vertical have metallic connections (5).

The electric circuit is represented in Figure 5.

This model, as well as those described in previous works, is supposed to operate in liquid dielectric, namely kerosene.

The stator and rotor were mounted in an iron tank, 18 cm in diameter and 20 cm high.

The rotor consists of 11 discs, each of them having 30 metallic sectors. Steel balls were connected in a special housing and on springs to the upper disc. The balls slid on steel trays 7 and 8 during rotation of the rotor. The discs were put on ebonite tube 10, in the middle of which passed steel axis 11. The axis passed through the ball bearings; one end, to which a pulley is attached, passed through an aperture in the upper ebonite cover of the tank. The discs of the stator had 20 small sectors and two big ones (A and B). Each disc was cut along the line a - b, in such a way that a previously assembled stator could be dismantled along this plane. All sectors of the stator along one vertical were connected by metal. Consecutive sectors of the stator were connected by high-ohmic resistances of the order of 10^9 ohms. The resistances were prepared from paper soaked with India ink and then covered with a protective layer of shellack.

The stator and rotor were assembled outside the machine and then installed in the iron tank.

Between the first and second upper discs of the stator, movable steel trays were attached in such a way that the steel balls of the tenth disc of the rotor could slide along the trays only during rotation, in which case the balls compelled by centrifugal force pass beyond the surface of the rotor.

The primary charge was transmitted to the steel tray 7; it was then discharged by tray 8; and the secondary potential was led out through the ebonite insulator. The sectors of stator A were grounded and the sectors B were connected to the trays 8 and constituted the high-voltage electrodes.

Every sector of the rotor located between the grounded sectors of the stator A forms a condenser. The total capacity of the system equals the sum of the capacities of the sectors of separate discs.

In this way we get a well developed surfaced of the rotor, allowing a multiple increase of the operating surface (in comparison with previous models) and a consequent increase of the charging currents.

On the opposite side the sectors of the rotor, falling between the big sectors of stator B, resemble a Faraday pail and give off their charge, thus continuously increasing the potential of the sector B.

We consider as another advantage of the new model the smooth gradation of potential. Between the high-voltage sectors B and the grounded sectors A a strong resistance is inserted with side-connections to each sector. If the resistance inserted between two consecutive sectors equals r_i, then the difference of potential between them will be

$$V_i = I_r r_i$$

where I_r is the total leakage current of the resistance, the value of which is determined by the relation

$$I_r = \frac{V_r}{\Sigma r_i}$$

Any difference of potential can be established between consecutive sectors, its value being limited only by the rupture voltage across the gap between the sectors.

A similar distribution is automatically established between sectors of the rotor if the gap between the rotor discs and stator discs is kept constant, since the charge of all rotor sectors is the same and constant, the electric field between rotor sectors and stator sectors is the same too; therefore the potential of a rotor sector will always be the same amount higher than the potential of the corresponding stator sector. The difference of potential between them maintains everywhere the value assigned at the start of the charge.

One more advantage of this construction, in comparison with previous models, is that we can create a nearly constant and homogeneous electric field between the rotor plates and stator plates, which enables us to raise the operating potential of the electric field up to the value of the rupture voltage.

3. RESULTS OF TESTS

The principal aim of the small model was to check the possibility of one's obtaining strong currents with a highly enlarged area of rotor and stator. We measured the maximum currents (short-circuit currents) and the dependence of primary potential V_1 (for constant rotation) on number of revolutions n (for V_1 = const.).

The results are represented in Figures 6 and 7, where the rectilinear part of the characteristics shown and the numerical values agree with computed data.

The ratio of maximum to minimum capacity was determined from readings of external characteristics of the models:

$$\frac{C_1}{C_3} = 6.8 .$$

It was found that the high-voltage sector, different from a Faraday pail, did not secure adequate discharge from the discs. This disadvantage originated from the system of connections of the rotor sectors along the vertical. One part of a rotor sector and the conductor (5) connecting it (Figure 4 and 5) protruded from the stator and retained a considerable charge. This defect could not be corrected because of the model's small size.

In order to control the operation of resistances distributing the potential along the stator, we measured the distribution of potentials during operation of the model as well as with an immobile rotor. Even in the case where the leakage current through the resistances did not exceed 1% of the current transmitted by the plates during the rotation of the rotor, the distribution of potentials, with rotor rotating or not, did not exceed the tolerances. In this way it was found that even in the case of low current in the distributing resistances, the charge induced in the stator sectors by the rotating rotor discs does not introduce essential distortions in the potential of the stator sectors.

4. DOUBLING OF THE CHARGING CURRENT

The operating part of the above-described model, as well as that of previously described models, was only a half of the rotor, namely between the part receiving the charge at low voltage V_1 and the terminal discharger at high-voltage V_2 on the diametrically-opposite side of the rotor. In order to use the second half of the rotor, we transmitted to the rotor sectors after they had yielded their charge to the high voltage sector a charge of opposite sign, which they transmitted after half a rotation to the grounded stator sector.

For this purpose an additional tray was installed in the region of the high-voltage sector of the stator B, connected to the sector B by a suitably-chosen resistance. Figure 8 shows a diagram of the current doubling and the measuring part of the system.

As is seen from this diagram, the potential of tray a is smaller by IR than the potential of tray 8; thus the rotor plate which contacts tray a is charged negatively (Note: We assume that the primary charge is positive.)

relative to sectors of stator B. This negative charge is transmitted by rotation of the rotor, and the corresponding positive charge is transmitted to the high-voltage circuit. The operational conditions will be optimum when IR = V_1; then the negative charge emitted will have the same value as the supplied positive charge. In this case we should obtain a double charging current.

With the given model we reached only a 45% increase of current; but we did not require more than a basic check of the diagram of charge transmission, because deficiencies due to this model's small size compelled us early to design a bigger model.

5. BIG TWO-DISC MODEL WITH 30 SECTORS

In the new model we decided to achieve greater perfection of high-voltage performance by way of better charge transmission. For this purpose it was necessary that the rotor's metal sectors enter completely between the stator's high-voltage sectors; but we were compelled to give up the metal connections between the rotor sectors located along the axis, because such connections necessarily protrude from the stator sectors. We had to arrange instead a separate inlet and outlet of charge for each disc.

In order not to complicate the model with commutators we decided on a two-disc rotor.

The model was designed for operation in gas under pressure. A two-disc model was assembled in an iron tank 300 mm tall inside and 700 mm in diameter inside. An ebonite insulator 90 mm in diameter able to transmit a voltage up to 200 kV passed through the gasket in the tank's side wall. The rotor's axis passed through the gasket in the tank's cover. The pressure inside the tank could reach 4 - 5 atmospheres.

The rotor discs were made of ebonite sheets 10 mm thick. We set 30 bushings into the periphery of each disc. Steel balls were attached with springs to the bushings; during rotation the balls projected out from the disc surface and rolled on steel trays attached to the stator. The whole surface of the discs was first coated with metal (by metal spraying) and then a part of the coated surface was grounded; channel-like grooves separating the disc into 30 equal sectors were milled. The exterior radius of the sectors was 245 mm, and the interior radius was 80 mm.

The sectors were made up of separate aluminum sectors, and each disc consisted of 20 small and 2 big sectors. The stator consisted of 3 discs in such a way that each rotor disc was located between stator discs. The gaps between discs were 5 mm. The external radius of the stator sectors was 280 mm, the interior 72 mm; the stator sectors covered the rotor sectors from the inner and outer side.

Inside the big grounded sectors of the stator were attached insulated steel trays which received the primary voltage V_1. Inside the big high-voltage sectors two pairs of steel trays were set - one pair fortaking off the charge the second for transmitting the charge.

On the exterior surface of the stator, steel bridges connected corresponding sectors of various stator discs. Between the bridges, resistances were fixed for the distribution of potential between consecutive stator sectors. Total of 22 resistances were used, each of 10^{10} ohms. The big high-voltage sectors had metallic plates on the generating surface, covering the whole space between the sectors; it was supposed to be a good approximation to a Faraday pail.

Figure 9 shows the exterior characteristic for $V_1 = 1.5$ kV, n = 1200 rev/min and p = 1 atm. The slope of the characteristic proves that this model approaches considerably a Faraday pail; the extrapolated value is $V_{max} = 130$ kV; hence: $C_1/C_3 = V_{max}/V_1 = 87$.

For p = 1 atm, however, we do not reach a potential of 130 kV. At approximately 50 - 60 kV the corona effects sets in and thus prevents further increases of V_2. The peak voltage V_n reached only 60 - 65 kV.

It should be noticed that in this model we were unable to raise the primary voltage V_1. At p = 1 atm and already at V_1 = 2.5 kV, breakdown discharges occurred between the stator sectors and rotor sectors, due to inadequate choice of the numbers of stator sectors.

At V_2 = 60 - 65 kV the voltage drop between consecutive sectors reached ΔV = 6 kV. Let us assume that we transmit to a rotor sector a charge at voltage V_1. When the rotor sector is located exactly under a stator sector, its potential is really higher by V_1 than the potential of the stator V_1. But when the rotor sector thereafter enters the next stator sector with a higher potential $V_1 + \Delta V$ and enters almost entirely into the stator sector with potential $V_1 + \Delta V$, its own potential nearly reaches the value $V_1 + \Delta V + V_1$, while its edge only gets out from the sector with potential V_1. The potential difference between then is $\Delta V + V_1$. If V_1 = 2.5 kV and ΔV = 6 kV, the potential difference between rotor and sector can reach at some moment the value

$$V_1 + \Delta V = 8.5 \text{ kV} .$$

For a gap δ = 0.5 cm, taking the marginal effect into consideration, we can easily account for the rupture between rotor and stator.

The described conditions are very disadvantageous for the obtaining of strong currents; indeed, if we assume that as in our case (p = 1 atm) the maximum permissible potential difference between rotor and stator is 8 kV, we can use only 2.5 kV for charge transmission. It is obvious that for an efficient operation of the machine, we should have

$$V_1 \gg \Delta V .$$

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The machine's characteristics were measured for various pressures up to p = 4 atm. Figure 10 shows the dependence of peak secondary potential on pressure. As is seen, divergence from proportionality occurs beyond 2 atm; this proves the considerable inhomogeneity of the electric field between the high-voltage construction and tank wall. The peak secondary potential at p = 4 atm was V_2 = 160 kV.

6. BIG TWO-DISC MODEL WITH 120 SECTORS

In order to eliminate the above-mentioned deficiencies, we constructed new rotor and stator and mounted them in the same tank. The dimensions of this model were the same as those of the previous model.

The rotor consisted of two ebonite discs, the surface of which was metal coated (by spraying); grooved channels divided each disc into 120 sectors. Because the previous commutators were complicated, we changed to a charge transmission utilizing the corona effect. The commutators were a series of steel needles, fixed 0.5 - 1 mm distance from the rotor. A total of 3 pairs of corona brushes were installed: one pair in the grounded stator sector for supply of charge was connected with the primary voltage; the remaining two pairs were located in the high-voltage stator sectors and were used for the taking-off and supply of charge of opposite sign. The transfer from direct-contact transmission to corona-brush transmission should allow one to increase the rotor's linear velocity; for stronger construction, therefore, we made the rotor axis of steel and surrounded it with a thick ebonite sleeve.

The stator was assembled from sprayed ebonite discs, each separated into 80 small and 2 big sectors. Between the big stator sectors (high-voltage and grounded sectors) 40 small sectors were installed on each side.

At V_2 = 60 kV, ΔV is 1.5 kV. If the permissible potential difference between stator and rotor is again 3 - 8.5 kV, then V_1 may reach 6 - 6.5 kV and the condition $V_1 \gg \Delta V$ may be satisfied, with charging currents increased. In order to distribute the potential among the stator sectors, we inserted 82 resistances. For convenient control of the brushes the space between the high-voltage stator sectors on the exterior side was not shut off, although this circumstance somewhat deteriorated conditions governing the taking-off of the current.

Even the first readings proved that increasing the number of sectors produced higher charging currents; at p = 1 atm the primary potential could be raised to V_1 = 5 kV, i.e. nearly to the planned pre-determined value; with favorable charge transfer, p = 4 atm and rotational speed n = 1200 rev/min, peak currents (short-circuit currents) reached 0.5 - 0.6 mA.

It should be noticed that the presence of a large number of distributing resistances and their insertion increased the number of sharp edges and thus deteriorated the corona effect; hence in the first tests at p = 4 atm we could obtain secondary potential of only V_2 = 125 kV.

In the next tests we modified the connections in the stator sectors and the location of distributing resistances, thus considerably decreasing the corona effect and enabling us to obtain a secondary potential of V_2 = 160 kV (at p = 4 atm). Direct readings of the short-circuit current with and without transfer of charge proved that we had completely doubled the current; in addition the computed values of the current, taking into consideration the doubling of the charge at transfer, entirely agreed with the experimental values..

The stage of minimum capacity in the high-voltage system was not yet completely established; in these tests we had the ratio:

$$\frac{C_1}{C_3} = 20 - 21 .$$

In order to clarify whether the corona brushes completely give up the charge, we made control tests by replacing the points by especially made contact brushes. But the ratio $\frac{C_1}{C_3}$ remained nevertheless equal to 21; such a low value is probably due to the imperfect Faraday pail in the high-voltage system.

Before the start of third series of tests, further modifications in construction were made in order to improve the system of high-voltage electrodes and to decrease the corona in the tank, the latter effect limiting the peak current.

By radically changing the connections between stator sectors and screening the distributing resistances and also by preventing the corona effect on the axis and stator bearings, we succeeded in raising the peak secondary voltage, first to 175 kV and later to 210 kV.

The improvement of the high-voltage system in the sense of better approximation to a Faraday pail allowed us to raise the ratio C_1/C_3 first to 30 and later to 49.

The summary of results is represented in Figure 11, where the curves 1, 2, 3 and 4 represent the exterior characteristics with successive decrease of corona effect and increase of the ratio C_1/C_3; as shown in the introduction (Figure 2) the decrease of capacity C_3 allowed us to increase considerably the machine's efficiency while increasing the supply charge at a given operating potential V_2.

The gradual elimination of spots with particularly sharp corona effect led to a considerable increase of the peak potential attained by the machine, from 125 kV to 160 kV and later to 175 kV and 210 kV. The latter voltage was obviously limited by the corona effect at the potential output.

The above mentioned peak voltage V_2 pertains to idlerun operations without exterior charge. At a charge of 0.2 - 0.3 mA (in the X-ray tube) the secondary potential reached V_2 = 160 - 170 KV (for primary voltages equal to 13 kV).

We express our gratitude to mechanists F. A. Nikolayev and D. Goncharenko and to laboratory assistant A. N. Voronin, who took an active part in the construction, assembly and tests of the models.

7. SUMMARY OF RESULTS AND CONCLUSION

Three multi-disc high-voltage electrostatic generators were tested (a small 11-disc model operating in kerosene, and two big 2-disc models in compressed gas).

1. The models consisted of a rotor assembled from separate discs, which rotated between immobile discs of the stator. Metal-coated sectors were fixed on the discs, and the desired potential distribution was obtained among the sectors by means of distributed resistances, thus securing a sufficiently homogeneous electric field on the periphery of the stator.

2. Readings of peak charge currents (short-circuit currents) showed good agreement between computed and experimental data; the measurements of exterior characteristics showed agreement between experimental and computed characteristics.

3. Conditions governing the number of sectors on the machine discs were clarified; it is required that the potential difference between consecutive stator sectors (ΔV) be considerably smaller than the primary potential difference V_1 ($\Delta V \ll V_1$). This condition was thoroughly proved by the transition from a 30-sector machine to a 120-sector one.

It was verified that the resistances distributing the potential between the stator sectors operated satisfactorily.

4. The system of current doubling was checked by charging the rotor sectors with a charge of opposite sign at the high-voltage sector in the transmission sector by means of additional commutator equipment and with special additional resistances. For operation in gas or compressed gas the complicated equipment of contact brushes was replaced by corona points, which considerably simplified the construction of the machine.

5. The exterior characteristics of big models operating in compressed gas were tested. It was proved that the gradual elimination of points with corona effect in the high-voltage system and the decrease of minimum capacity C_3 at the take-off of the charge (increase of the ratio C_1/C_3) raised the maximum charge of the model and its efficiency, thus allowing strong charging currents for a given potential or a higher potential for a given current.

6. The potential of the two-disc 120-sector model under idle-running operation was increased from 125 to 160 kV, later to 175 kV and finally to 210 kV. The latter was limited by the corona effect at the output terminal. For a charge of 0.2 - 0.3 mA the secondary potential reached V_2 = 160 - 170 kV at a primary voltage of V_1 = 13 kV.

7. Tests proved that the multi-disc electrostatic generator may be a source of not only high-voltage, but also strong currents. In the construction of high-voltage electrostatic generators operating in compressed gas, most consideration should be paid to the following two conditions:

a) The high-voltage system should secure as full as possible electrostatic shield forthe entering sectors of the rotor.

b) It is necessary to eliminate very carefully the points producing the corona effect in the tank and to obtain a field as homogeneous possible.

At present we are testing in our laboratory a multi-disc generator, designed to have a potential around 700 kV, of somewhat modified construction.

Results of investigations agree completely with the above-expressed conditions.

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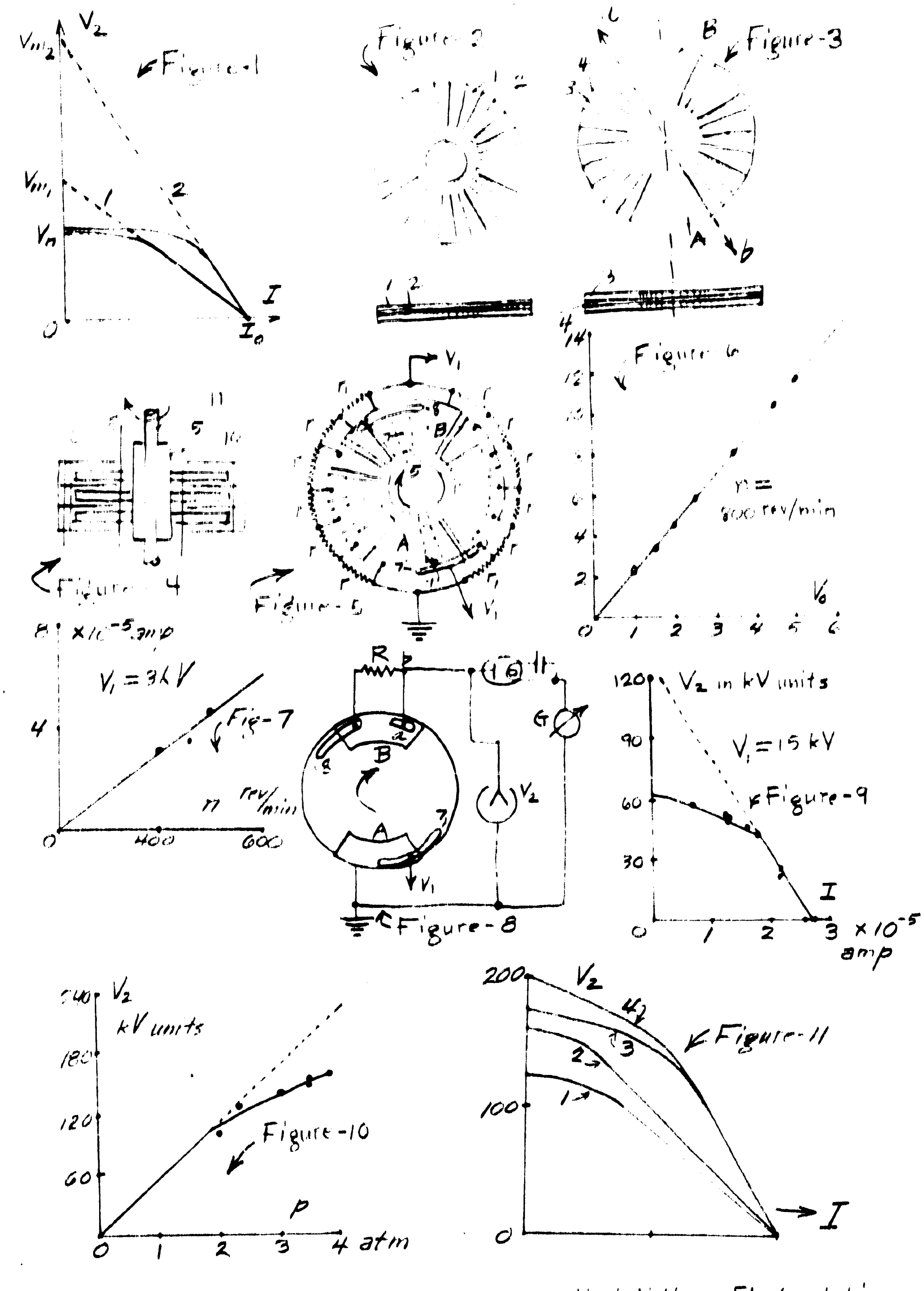

11 figures from "Models of Multidisc High Voltage Electrostatic Generators" by Gokhberg, Ioffe, & Reynov, in ZhTF Vol IX No. 23 Dec 1939, pp 2094-2103.