Title: MODELS OF HIGH-VOLTAGE ELECTROSTATIC GENERATORS OPERATING IN A FLUID DIELECTRIC by B. M. Gokhberg, A. F. Ioffe and M. M. Reynov (Russia)

Source: Zhurnal Tekhnicheskoy Fiziki, Vol IX, No 23 (Nov or Dec 1939) pp 2081-2089 (Russian monthly periodical)

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MODELS OF HIGH-VOLTAGE ELECTROSTATIC GENERATORS OPERATING IN A FLUID DIELECTRIC

[NOTE: The following is a translation of a Russian article appearing in the Zhurnal Tekhnicheskoy Fiziki, Vol IX, No 23, Nov/Dec 1939, pages 2081-9, which was submitted 4 October 1939. The authors are B. M. Gokhberg, A. F. Ioffe, and N. M. Reynov, who are affiliated with the Leningrad Physical Technical Institute of the Academy of Sciences USSR.]

[Summary]

In this work the authors describe the results of investigations of three models of electrostatic generators that operate in a fluid dielectric, namely kerosene. The greatest voltages obtained in the described models were: 1) Small unirotor model V_n = 95 to 100 kv; 2) small birotor model V_n = 80 to 90 kv; and 3) middle-size unirotor model V_n = 150 to 170 kv.

1. Introduction

The operating principle of electrostatic machines whose models will be described below consists in the main of the following: by varying the capacitance of the charged conductor and expending a corresponding amount of mechanical work, we transfer a given charge with an initial lower potential to a higher potential.

In our models the operating cycle consists of the four stages:

1. The imparting to a moving plate (robor) of a charge Q at a low primary voltage V_1: $Q = C_1V_1$.

2. The moving plate is disconnected from the source of voltage V_1 and decreases the capacitance to the value C_2; whereupon the potential of the charge Q increases from V_1 to V_2 (V_2 is the secondary voltage).

3. The decrease of the capacitance from C_2 to C_3 at constant potential V_2 transfers part of the charge q to the high voltage circuit:

$$q = Q - C_3V_2 = (C_2 - C_3)Q/C_2$$

4. By discontinuing the connection with the high-voltage circuit and increasing the capacitance to the value C_4, we lower the potential of the charge remaining on the plate (Q - q) to the original value V_1.

Then follows the first stage once more: at capacitance C_4 the plate is connected with the source of the primary voltage V_1; the increase of the capacitance from C_4 to C_1 imparts to the plate an additional charge q, but the total charge again becomes equal to Q.

During one operating cycle a charge q at potential V_1 is imparted to the conductor (plate of the rotor), and the same charge is transferred to the high-voltage network at a potential V_2. The electrical energy obtained during the cycle $W_2 = qV_2$ is defined as the sum of the mechanical work $A = q(V_2 - V_1)$ expended in the transference of the charge from potential V_1 to V_2 and the electrical energy $W_1 = qV_1$ obtained from the primary circuit:

$$W_2 = A + W_1 \qquad (1)$$

In the case where the secondary voltage is much greater than the voltage of the primary circuit V_2/V_1 1, all the energy W_2 is practically received on account of the mechanical work ($W_2 \approx A$). (NOTE: The machine is therefore a generator and not a transformer of electrical energy.)

If n cycles per second are completed in the machine, then the current ~~strength~~ in the high-voltage network is determined by the following relations :

$$I = nq = (C_2 - C_3)Qn/C_2 = (C_2 - C_3)C_1V_1n/C_2 \; . \qquad (2)$$

The greatest possible potential V_{max} of the machine is determined by the least capacitance C_3 from the relation: $C_1V_1 = C_3V_{max}$. (3)

The dependence of the secondary voltage of the machine upon the load current in the high-voltage network (that is , the external characteristic of the machine) can be represented by the following equations :

$$V_2 = V_{max}(1 - I/I_0) \qquad (4)$$

$$\text{or } I = I_0(1 - V_2/V_{max}), \qquad (4a)$$

where $I_0 = C_1V_1n$ is the maximum current (short-circuit current, when $V_2 = 0$), and V_{max} is the maximum voltage (no-load voltage, when $I = 0$).

Dependence (4) is represented in figure 1a; whereupon it should be noted that this dependence is obtained on the assumption that the maximum potential $V_2 = V_{max}$ is determined only by the minimum capacitance C_3 (from relation (3)). In fact the maximum potential is often limited by the corona effect or the leakage current through the dielectric surrounding the rotor and through the high-voltage system of the machine . When leakage is present, the limiting secondary voltage V_n is determined by

$$V_n = I_f R_f \; , \qquad (5)$$

where I_f and R_f are the current and the resistance of the leakage. The characteristic of the machine varies; besides the characteristic represented in figure 1a, we obtain the [dependence] expressed in figure 1b; here with decrease of the load current as the value V_2 approaches V_n (in consequence of the sharp increase of the leakage currents) futher decrease of the current strength does not lead to significant increases of V_2. For such a characteristic the most convenient condition of operation will be the load I_m , when the voltage V_2 is close to V_n and the product I_mV_2 has a maximum value (see figure 1b).

When capacitance C_3 ~~tends to~~ [converges toward] zero, V_{max} ~~tends to~~ [converges toward] infinity. (Note: The condition $C_3 \to 0$ will hold when the high-voltage electrode receiving the charge of the moving plate forms a perfect Faraday pail and provides for the full removal of the charge passing through the high-voltage network.) In this case, decreasing the leakage through the dielectric and the corona effect, the external characteristic must have the form represented in figure 1c where the secondary voltge V_2 equals the limiting voltage and almost does not depend upon the load up to $I = I_0$. When the load current is close to I_0, and we have $V_2 \approx V_n$, we will receive the optimum conditions of operation of the machine.

In the design of a machine, therefore, one must aim for a possible decrease of the capacitance C_3 , which approximates the external characteristic represented in figure 1c, and the optimum current of the load approximates the maximum current, namely the short-circuit current.

Below we describe briefly several models designed by us of electrostatic generators and the results obtained from their tests.

2. Small Unirotor Model

The ~~theoretical scheme of~~ [main diagram for] this model is ~~represented~~ [shown] in figure 2. Inside the immobile grounded metal cylinder 1 an insulating cylinder 2 is placed eccentrically, [and] on ~~whose (i.e. cylinder's)~~ [its] surface are fastened metal plates 3, insulated from each other. The charge is supplied by brushes to the part which corresponds to the least capacitance C_3 of plate 3 relative to the ground. The capacitance C_3 decreases considerably if one installs another immobile metal electrode encompassing part of rotor 7 (high-voltage screen), connected to the high-voltage brush (that is, the electrode).

Such a screen [shield] possessing the same potential as the plate in contact with it sharply diminishes the plate's electrical capacitance C_3 .

The model was designed for operation in a liquid dielectric, kerosene, which permits one to raise considerably the maximum strength of the electric field in comparison to that allowed by air (especially in small machines). The model consisted of an iron cylinder 1, diameter 18 cm and height 18 cm, within which a rotor 2, diameter 9 cm and operating height h=9cm, rotated. Through stuffing-box openings in the lateral surface of the cylinder were passed two rods, with grounded screens fastened to them, with the aid of which (i.e. rods) the gap between the rotor's plates and the screen could be regulated. The primary voltage V_1 was introduced through an ebonite lead 9 passing the stuffing-box opening 8. The secondary was led in through an ebonite insulator 11 passing through the stuffing-box opening 10. In all, 20 aluminum plates were disposed along the rotor; ~~hence~~ the width of the gap between the plates approximately equalled the width of the plates -- thus the surface of the plates equalled half of the lateral surface of the rotor.

The supplying and the removing of the electric charge from the rotor's plates was carried out with the aid of a special system of contacts. To each rotor plate was fastened a small ring with movable ball which projected from the ring during rotation of the rotor, being pressed by centrifugal force to the outer edge of the ring. To the input and output leads were attached brushes 4 and 6 with a considerable number of steel conductors, along which the jutting steel balls slid.
Cylinder 1 was covered with two ebonite covers with rubber (gasoline-resistent) packings which prevented the leakage of the kerosene. The shaft passed through the upper cover, at the end of which ~~(i.e., shaft)~~ was attached a pulley connected to an electric motor with 25 watt power. During operation in kerosene the rotor rotates at ~~with~~ about 1400 rev/min.

In the course of investigations we discovered the great influence of the curvature of the grounded screen encompassing part of the lateral surface of the rotor; namely, the field at the surface of the rotor (and also near the grounded screen) had to be as homogeneous as possible. In this case one could operate the machine at great field intensities close to the rupture value and concentrate on the plates of the rotor a maximum charge without the danger of rupture occurring. By selecting the proper shape for the surface of the grounded screen, we reached satisfactory results for small gaps between the screen and the rotor and could raise the electric field strength to 120 - 150 kv/cm (for a rupture strength of the kerosene equal to 200 - 220 kv/cm).

Figures 3 and 4 show the characteristics measured by the models for the following conditions : 1. the coefficient of filling of the lateral surface of the rotor was $\alpha \approx 0.5$ (that is, the ratio of the surface of the aluminum plates to the total surface of the rotor) and 2. the gap between the rotor and the grounded screen was $\delta = 0.4$ mm.

The secondary voltage V_2 was measured by means of a sphere gap. The model was loaded by ~~round spark detector. The charge of the model used in~~ an x-ray tube and the current strength of the high-voltage circuit was regulated by the incandescence of the cathode in the x-ray tube. Thus we were able to measure in parallel the current strength in the secondary circuit and the voltage V_2 ; that is, we could measure the external characteristics of the model. Figure 3 gives the characteristics for V_1 equal to 2,3,4,5,6 kv.

The results of experiments show good agreement with computations of the external characteristic. Only in two characteristics, for $V_1 = 5$ and 6 kv, which give considerable secondary potentials V_2, do leakages and ~~the~~ corona effect begin (but even here we did not reach the characteristics shown in figure 1b).

From the adduced characteristics it follows that the ratio V_{max}/V_1 is about 20 and hence we obtain according to formula 3 the ratio of the maximum capacitance C_1 to minimum C_3 ; namely $C_1/C_3 \approx 20$.

Figure 4 gives the dependence of the short-circuit current I_0 upon primary voltage V_1. The dependence coincides with formula 2.

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For the sake of control checks let us conduct a comparison of the calculated data for I_0 with the experimental data.

I_0 was calculated according to the following formula:

$$I_0 = (hv\varepsilon/4\pi)(V_1/\delta)\alpha, \qquad (6)$$

where alpha is the coefficient of filling as defined above; h is the operating height of the rotor ; v is the linear velocity at the surface of the rotor; epsilon is the dielectric constant of the kerosene; and delta is the gap between the rotor and screen.

Within the limits of possible errors the experimental data coincides with the computed data: For V_1=4kv, I_0=$4.8\cdot10^{-5}$amp (computed) and $5\cdot10^{-5}$amp (experimental); for V_1=6kv, I_0=$7.2\cdot10^{-5}$amp (computed) and $7.2\cdot10^{-5}$amp(experimental). The greatest voltage which we received on this model was 95 to 100 kv.

3. The Small Birotor Model

Like the unirotor model the birotor model was designed for operation in fluid dielectric; namely, in kerosene.

The basic elements of the model's design and construction are shown in figure 5, which gives a cross-section of the model's plan view.

The model consisted of an iron cylinder 1 diameter 23 cm and height 19 cm , within which two small rotors rotated toward each other.

The rotors of model 2 are small ebonite cylinders with upper covers. In the cover was attached a roller with the aid of which the rotors were brought into rotation . To the cover of the rotors were attached geared wheels for the mutual rotation of the rotors. The gears were made of ebonite in order that the charge would not discharge from the high-voltage part of the rotor to the low-voltage part. Each roller connected with a rotor passed through two ball bearings; one of the rollers passed the upper cover enclosing the iron container 1 and to its end was attached a pulley.

On the lateral surface of a rotor was milled continuous grooves into which aluminum plates were inserted so that the internal and the external lateral walls of the rotor possessed surfaces alternately metal and ebonite. Near each rotor were four screens; external grounded screen 5, external high-voltage screen 7, internal grounded screen 8, and internal high-voltage screen 9.

The primary voltage V_1 was introduced through the ebonite leads 10 passing through the stuffing-box openings 11. The secondary voltage V_2 was introduced through ebonite insulator 12 passing through stuffing-box opening 13.

The supplying and removing of the electric charge from the rotor plates was effected with aid of a new original design for contacts. In each metal plate of the rotor was tightly screwed in a ring attached by a small spring. A movable ball moved freely on the movable ring. During rotation, the ball was pressed to the outer edge of the movable ring and began to draw the ring outward until the centrifugal force was in equilibrium with the force of the deformed spring. Close to the rotor near the grounded and high-voltage screens were attached steel arched pans (4 and 6), which could be installed so that the steel balls jutting out during rotation slid against the pans. The force of the spring was almost in balance with the centrifugal force; this apparatus permitted one to eliminate the abrupt collisions of the balls against the pans, and at the same time it ensured the desired contact between them. The pans on the grounded screens were connected with the primary voltage V_1. The pans on the high-voltage screens were connected with them and with the high-voltage input leads.

Cylinder 1 was covered with two ebonite covers with rubber stuffing . The model was brought into rotation by a 25-watt electric motor.

This model, in comparison with the unirotor model, possessed the following advantages:

1. The charge was disposed both on the external and on the internal surface of the metal plates of the rotor (in consequence of the installation of the internal grounded screens); thus the maximum initial capacitance C_1 was increased twice .

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2. The connection of the internal high-voltage screens 9 to the external screens 7 made the high-voltage system approximate a Faraday pail. In the passage of the plates in the hollow between the external and the internal high-voltage screens a more complete removal of the electric charge was ensured in consequence of the significant decrease of the minimum capacitance C_3.

3. The presence of two rotors led to a more symmetrical picture of the electric field distribution and to an improved utilization of the internal space in the model (it is obvious that in this sense still better results could be expected for three or four-rotor system).

Investgations of this model were conducted with three different arrangements:

1. The external grounded and external high-voltage screens were installed; the internal grounded and the internal high-voltage screens were absent (this arrangement corresponded to the operation of the unirotor model).

2. The external grounded screens , the external and internal high-voltage screens (an approximation to the Faraday pail -- namely a decrease in the capacitance C_3) were installed.

3. The external and internal grounded screens and the external and internal high-voltage screens were installed. In this case, besides the decrease in the capacitance C_3, the capacitance C_1 still increased in consequence of the introduction of the internal grounded screens.

In all three experiments the gap between the external grounded screen and the rotor was fixed at $\delta = 1.1$ mm. The internal grounded screens were fixed at approximately the same distance; it is necessary to note, however, that the accuracy of installation of the internal screens was not great and the gap could differ by 20 to 30 %.

Experiments with arrangements 1,2, and 3 were repeatedly conducted in various sequences and gave good reproducible results.

Some of the results of the measurements are shown in figures 6,7,8; the speed of rotation here for all the data was 680 rev/min.

Figure 6 represents two characteristics for $V_1 = 4$ and 6 kv (the first arrangement). The rectilinear dependences satisfy equation 4 (figure 1a); from the value V_{max}/V_1 one can determine the ratio of the maximum capacitance to the minimum, which turns out to equal $C_1/C_3 = 12$.

Figure 7 (the second arrangement) represents similar characteristics for $V_1 = 4.6$ and 8 kv. For $V_1 = 8$ kv we have already considerable influence of the leakage upon the magnitude of the secondary voltage V_2 ; in this case the characteristic is rather close to the form shown in figure 1b. From the slope of the rectlinear portions of the characteristic at I close to I_0 we determine the ratio V_{max}/V_1 and C_1/C_3, which turns out to equal $C_1/C_3 = 20$.

Figure 8 (the third arrangement) shows the characteristics for $V_1 = 4$ and 6 kv. From the slope of the rectilinear portions we determine the ratio $C_1/C_3 = 40$.

Thus the introduction of internal screens consequently increases the ratio C_1/C_3 from 12 to 20 and from 20 to 40; here the first increase is connected with the introduction of the internal high-voltage screens, which decrease the minimum capacitance C_3 (that is, the screens improve the removal of the charges in the high-voltage system), and the second increase is connected with the introduction of the internal grounded screens, which increase the capacitance C_1 , during supply of the charges from the primary voltage because of the increase of the operating surface of the metal plates of the rotor.

The greatest voltage which obtained in this model was 80 -90 kv. The greatest current , namely the short-circuit current, for $V_1 = 8$ kv and a speed of rotation of 1050 rev/min reached 0.1 milliampere, which coincided with the computed data.

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4. The Unirotor Model (Medium Size)

Like the small unirotor model a medium-size model was investigated by us, which also operated in kerosene.

The rotated rotor whose operating height was 50 cm and diameter 18 cm in an iron container 40cm in diameter and 60cm high. The general construction of the model was the same as the small model described in section 2 above.

Tests on the medium-size model were conducted in two directions; namely, investigations of its characteristics and the obtaining of comparatively hard x-rays.

Measurements were conducted both with a secondary-voltage output lead (which represented considerable convenience for the measurement of the external characteristics) and without the output of secondary voltage, when the x-ray tube was placed within the model. The second case has the advantage that the high voltage was completely absent in the operating area.

a) The secondary voltage is led out from the machines through an ebonite output lead. The ebonite outlet whose size was limited by the size of the outlet stuffing-box gave the first evidence of the corona effect for V_2 higher than 150 kv and did not permit the voltage to be raised above 180 kv.

Several external characteristics for various V_1 are shown in figure 9; here the numerical results for the maximum currents (namely short-circuit currents) are in agree- with the computed data.

For an electric field near the grounded screen equal to 60 kv/cm, the maximum current reached 0.25 milliampere.

The ratio of the maximum capacitance C_1 to the minimum C_3 in this model was C_1/C_3 equal approximately to 48.

All external characteristics were taken by loading the model with the x-ray tube, from which we obtained an intensive beam of x-rays.

Measuring, with an ionization chamber, the coefficient of absorption of the hardest incident x-rays, we were able with respect to the magnitude of the absorption coefficient to determine the wavelength of the limits in the continuous spectra and thus we were able also to measure the voltages in the x-ray tube. We verified this method under the conditions governing the operation of the model for the output voltage and decided to use it in measurements of the secondary voltage, when it is not led out and the x-ray tube is located within the model .

b) The secondary voltage is not led out; the x-ray tube is located within the model. The x-ray tube was located in the outlet place and was passed through the stuffing-box opening in such a way that the external electrode of the anticathode in the tube was within the model and connected with the high-voltage system, and the surface of the anticathode was near the end of the stuffing-box opening outside the model's housing.

The x-rays obtained under these conditions gave great intensities, greater than for the output voltage, which indicated an improved utilization of the model (less leakage in consequence of the absence of lead output). From the measurements of the limits of the spectra we obtained the fact that the voltage reached 150-170 kv. It is necessary to note that the voltage obtained was limited by the surface charges on the glass of the x-ray tube used structural analysis (we employed an x-ray tube made by the "Svetlan" factory), and not by leakage in the generator.

In the work of assembling and testing the models, laboratory technician A. N. Voronin played a great role; to him the authors express their appreciation.

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5. Summary of Results

The authors investigated three electrostatic generators operating in a liquid dielectric, kerosene (namely, the small and medium-size unirotor models and the two-rotor model).

Measurements of the maximum load currents showed good agreement between the computed and experimental data. Measurements of the external characteristics showed complete agreement between the computed and experimental characteristics (namely, the dependence of the secondary voltage upon the load current).

The maximum possible secondary voltage is determined from the ratio between the maximum capacitance C_1 during supply of the charge from the primary voltage and the minimum capacitance C_3 during removal of the charge in the high-voltage system. If the secondary voltage V_2 reaches high values and leakage begins because of the corona effect or because of the surrounding dielectric, then V_2 will not attain the maximum possible values set by the ratio $V_{max}=(C_1/C_3)V_1$, but will tend to a certain limiting value which is determined by the resistance and the leakage current.

Particularly important and significant in the operation of the models is the matter of the arrangement of the high-voltage system where the removal of the charges takes place; the greater the high-voltage system approximates the conditions found in the Faraday pail, that is the less the residual capacitance C_3 , the higher the effectveness of the machine's operation. In the models under investigation it was successfully shown that one can decrease condiderably the capacitance C_3 with the aid of the internal screens and increase the amount of charge transported.

The maximum voltage attainable in the models were as follows:

a) small unirotor model : $V_n \approx 95$ to 100 kv,
b) small birotor model : $V_n \approx 80$ to 90 kv,
c) medium unirotor model: $V_n \approx 170$ to 180 kv,
(for a primary voltage equal to $V_1 = 6$ kv).

[9 figures appended]

- end -

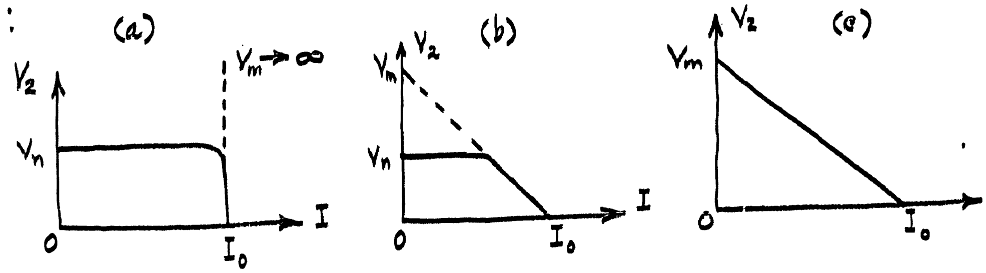

Figure 1

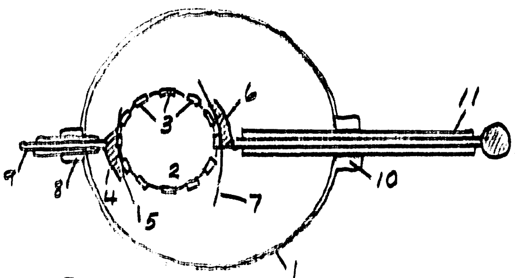

Figure 2

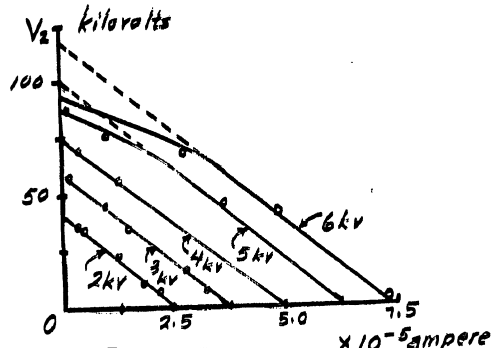

Figure 3

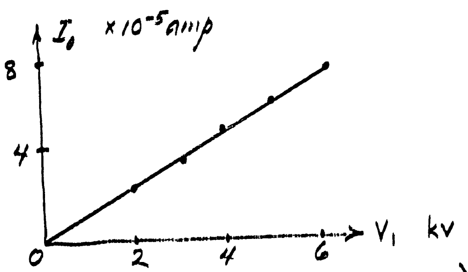

Figure 4

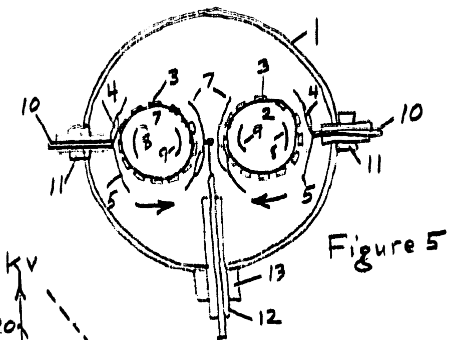

Figure 5

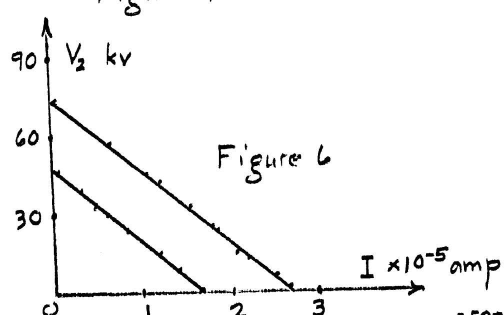

Figure 6

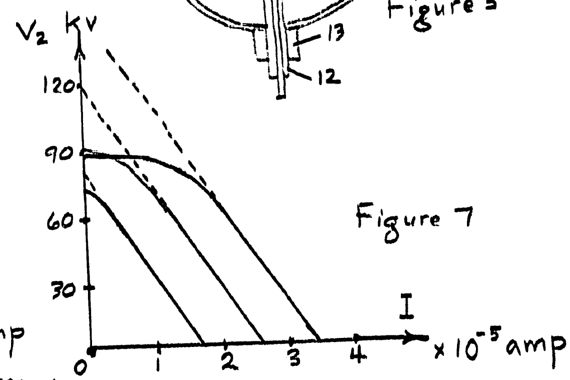

Figure 7

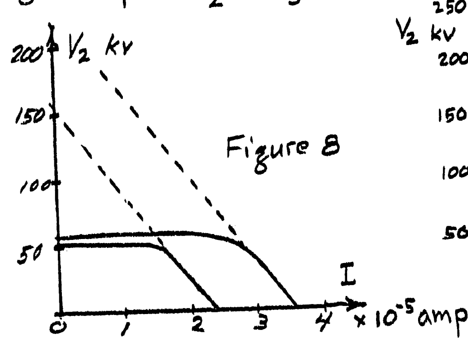

Figure 8

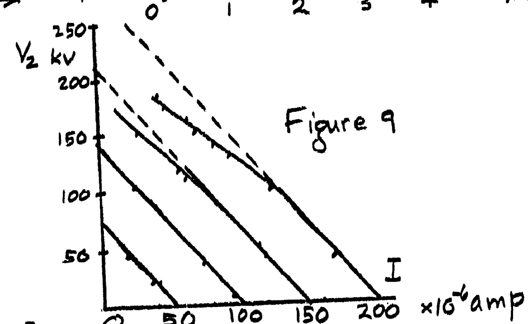

Figure 9