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CONFIDENTIAL

HIGH-VOLTAGE ELECTROSTATIC GENERATORS

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This article describes the construction of several types of electrostatic generators at the Ukrainian Physico-Technical Institute; some results of tests are cited, and ways for their further development are indicated.

1. INTRODUCTION

The problem of creating sources of dc voltage of the order of millions of volts is connected directly with the problem of investigating atomic nucleii by the method of bombardment with charged particles which have been accelerated in discharge tubes. However, this does not exhaust the possible applications of superhigh dc voltages, for such sources are of interest in connection with the solution of many other ~~other~~ electrotechnical problems.

At present the most common devices used as sources of high-voltage dc are those in which high-voltage ac is rectified and stepped up with the aid of different combinations of capacitors and tubes. In principle, by using capacitor-tube step-up circuits, one can obtain voltages as high as desired; in practice, however, these circuits usually attain voltages of less than 300 kv, and only in very rare cases do their voltages reach 600-800 kv. (Note: The conditions which prevent higher voltages from being obtained with capacitor-tube circuits are revealed in our article in Zhurnal Tekhnicheskoy Fiziki, 4, 1073, 1934.)

The many advantages of capacitor-tube circuits (such as relatively high power, ease of voltage regulation, and the presence in the circuit of points of intermediate potentials) cause these circuits to be considered as the most convenient sources of direct current up to 500,000 volts; but in the region of higher voltages the electrostatic generators are without doubt the most convenient, and for voltages of the order of 5 or more million volts, they are actually the only technically feasible source of high-voltage direct currents.

The electrostatic generator, which was first proposed by Van de Graaff (Van de Graaf, Compton and Van Atta, Phys Rev, 43, 149 (1933), suggests, through its principle of operation, the usual electrostatic induction machine but sharply differs from it in the form of its construction. Unfortunately, the literature lacks even the least detailed description of either construction data for different types of generators made by Van de Graaff and certain other American investigators or conclusions from the practical operation of these generators in the laboratory (Note: The sole exception is Bramhall's article (Rev Sci Instr, 5, 18, 1934), devoted to the description of a portable 500,000-volt generator; however, this article does not give an exhaustive presentation of either the constructional or operational data for the generator).

2. OBJECTIVES OF THE WORK

Having as our final objective the construction of a generator of maximum voltage possible within the limits of the size of the UFTI [Ukrainian Physico-Technical Institute] high-voltage room, we worked out two variants of this device: namely, a cascade capacitor-tube circuit with transformers fed by an insulating drive (Zhurnal Tekhn Fiziki, 4, 1077, 1934), and a single-pole electrostatic generator of the Van de Graaff type. Since our calculations have showed that with the same power and dimensions of the devices a voltage of the order of 2.5 million volts can be obtained in the first case, and 7 million in the second, we settled on the second variant and in the beginning of 1934 began designing this generator, whose construction is being completed at the present time. This generator will be described in a separate article. The problems of constructing certain assemblies for the large generator required careful experiments on models; as a result several generators of voltages of the order of 0.5-1 million volts were constructed. Certain of these were used to conduct experiments on particles accelerated in discharge tubes.

3. ELECTROSTATIC GENERATOR WITH CYLINDRICAL CONDUCTOR

A diagram of the first model constructed in UFTI is shown in Figure 1, and a photograph in Figure 2. The support consists of insulating boards 15 mm thick and 70-85 mm wide. On the insulating framework is placed a cylindrical conductor of plywood 3 mm thick, 1000 mm long, 720 mm in diameter, and with detachable copper hemispheres of the same diameter at each end. The apparatus for charging the belt and for removing charges from it is evident from Figure 1.

Different types of corona electrodes were tried, the best results being obtained with a metal tube 15 mm in diameter having a series of apertures bored at 25 mm intervals in which are placed the usual sewing needles. Satisfactory results were also given by electrodes made of wire 0.15-0.20 mm in diameter stretched parallel to the belt. Both the corona electrodes and the flat screens placed on the other side of the belt can be moved horizontally between the ebonite planks. (Good insulation of the upper corona electrodes and screens is essential for the normal operation of the generator). The belt transport rollers (100 mm in diameter) in this structure were turned from wood. They rotate together on their iron axles set in ball bearings and are driven by a 0.5 kw dc motor connected through a flexible coupling to the axle of the lower roller. The lower corona electrode was charged to 25 kv through a resistance of several megohms from an auxiliary high-voltage device.

The current obtainable from the generator is clearly equal to $I = 2\sigma \ell v$, where σ is the charge's surface density on the belt, ℓ is the belt's width, and v is its velocity. The coefficient 2 is explained by the fact that the belt is overcharged inside the conductor when we used this construction of corona electrodes, as a result of which a double quantity of electricity is taken off the belt.

If the belt can be assumed to be a flat condenser, then the maximum charge density on it can be calculated from the relation $\sigma_{max} = \frac{E}{4\pi}$, where E is the initial electric field strength in air at atmospheric pressure.

Setting E equal to $30 \frac{kv}{cm}$ we obtain for σ a maximum value of $2.6 \cdot 10^{-9}$ coulombs/sq cm. Thus the theoretical value of the current obtainable from the generator turns out to be:

$$I = 5.2 \cdot \ell \text{ (cm)} \cdot v \text{ (cm/sec)} \cdot 10^{-9} \text{ amperes}$$

Since in this model the velocity of the belt did not exceed 9 meters per second and its width was 90 cm, a current of the order of 400 μa could be expected. Actually, the maximum current successfully obtained from the generator was only 220 μa; that is, 55% of the calculated value. We should note that not one of the generators which we built put out a current greater than 60-65% of the theoretical value. The discrepancy between theoretical and experimental values for the current must be attributed on one hand to insufficiently smooth belt surfaces and resulting local overvoltages of the field which lead to premature corona [redacted], and on the other hand to charge losses from the belt on account of the strong ionization created by the upper and lower corona electrodes.

The voltage obtained with this generator was 600 kv at the positive pole and 700 kv at the negative pole. It was limited not by the corona appearing on the spherical surfaces but by the brush discharge arising at the places where the insulating braces enter the cylindrical surface of the conductor.

Voltage was measured with the aid of "generating" voltmeters specially constructed for this purpose, of a design proposed by Kirkpatrick and Gunn. We used two types of voltmeters: a device with a flat rotor, operating on a two tube amplifier (Kirkpatrick and Miyake, Rev Sci Instr, 3, 1, 1932. Kirkpatrick, Rev Sci Instr, 5, 33, 1934. Gunn, Phys Rev, 40, 307, 1932. Harnwell and Van Voorhis, Rev Sci Instr, 4, 540, 1933); and a voltmeter with a cylindrical split rotor (Henderson, Goss and Rose, Rev Sci Instr, 6, 63, 1935) which was connected through a commutator directly with a galvanometer of sensitivity 10^{-7} amp/graduation. For calibration of the voltmeters we used a spherical discharge rod 72 cm in diameter (used in experiments with generators with spherical conductors) and measured the charge accumulated on the conductor with the aid of a ballistic galvanometer. The calibration revealed that our generating voltmeters have a strictly linear scale up to maximum voltages, provided that corona does not appear.

The basic defect in the first generator model was the inadequate strength of the silk belt, which frequently became wrinkled or folded etc., during operation. Moreover, since the generator was not suited to charging a discharge tube, we passed on to the construction of generators with toroidal conductors.

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4. GENERATORS WITH TOROIDAL CONDUCTORS

Since the space at our disposal (overall height 4.5 meters) forced us to select the vertical dimensions of the generator as economically as possible, we used a conductor of toroidal form (height of conductor 1200 mm, and diameter 2200 mm) in the next generator which we constructed. Generators with toroidal conductors are pictured in Figure 3, which is a photograph of an apparatus consisting of two toroidal generators operating onto a horizontal discharge tube. The conductors of these generators were a wood framework of meridional ribs braced with two massive wood rings and sheathed with lobes of sheet iron beaten by hand on special forms. The circular upper aperture was covered with a carefully fitted lid and served as an entry to the interior of the conductor for the experimenter; at the lower aperture the conductor was placed on a cylinder serving as an insulating support. All seams were carefully filled, after which the conductors were lacquered. In each of the generators a set of three steel rollers was installed in the bottom and the same number in the top; thus the charge was carried by three independent endless belts. The charging devices were somewhat simplified, since the rollers themselves were employed as one of the electrodes. The belts, 45 cm wide, were manufactured of surgical oil-cloth, which seemed to be a completely suitable material for this purpose. The belt velocity in these generators was small and under stationary operation did not exceed 8-9 meters per second.

Under these conditions currents up to 0.3 ma were successfully obtained with each of the generators. The maximum voltage produced by the generators (without the addition of the tube) reached 900,000 - 950,000 volts in each. The interior of the conductors was large enough to house an experimenter as well as the necessary apparatus inside of them.

5. THE DISCHARGE TUBE

For operation with toroidal generators we built a special discharge tube whose external form can be seen in Figure 3. Its schematic cross-section is shown in Figure 4. The tube, 3800 mm long, consisted of four individual glass cylinders (220 mm in diameter) made tight with picein and joined through intermediate steel disks and through a central coupling box with the evacuationpump's outlet. The tube was assembled while in a vertical position; then the tube was encased in a special assembly sheath of wood boards in a horizontal position and suspended from the ceiling on insulating boards which were fastened to wood hoops placed around the steel connecting disks. After the tube had been suspended the assembly sheath was removed. On the basis of previous experiments with the construction of this tube we considered it necessary, with the aim of eliminating premature discharges inside the tube, to subdivide it with metal diaphrams into separate cells. For this purpose holes 3 mm in diameter were drilled 70 mm apart along the axis and placed at an angle of 120° to each other.

Through these holes were inserted threaded screws, with the aid of which 47 diaphragms of sheet aluminum 3 to 5 mm thick, having 80 mm openings, were placed in the tube. (Note: Later it appeared that we chose the wrong material for the diaphragms, since aluminum corrodes under the influence of mercury vapors.) The places where the screws entered were sealed with picein. A spiral paper strip, impregnated with india ink, was wound around the outside of the tube and served as an ohmic voltage divider. All the diaphragms were connected to the corresponding points on the divider, with the result that throughout the tube a definite distribution of potential was maintained. The tube was faced with solid steel disks provided with openings for the sources of charged particles and instruments for experiments.

After all the picein seals were covered with a coat of bakelite lacquer a sufficiently high vacuum was successfully obtained in the tube. The pressure in it did not exceed 2 . 10^{-5} mm of mercury. The evacuation was carried through the grounded coupling box in the middle of the tube with the aid of a four-stage mercury diffusion pump made by the Leybold firm (Model E) which was provided with a large trap containing liquid air and a McLeod manometer. The original adjustment of the tube, which was done by repeatedly increasing the voltage of the generators, gradually, by regulating the velocity of the belt up to the moment of discharge in the tube, continued for 15-20 hours. Once adjusted, the tube could stay under pre-vacuum pressure for several days, after which it was brought to the working state by relatively brief adjustments in the course of 2-3 hours. Both ends of the tube were inserted into the conductors through openings about 30 cm in diameter. The edges of the openings were specially rounded and all sharp bends were smoothed from the tube's insulating supports with the help of special cover plates; (and the wood coupling boxes) nevertheless, coronas and "flares" (brush discharge) could not be averted from appearing in the places where the tube entered the conductors. Therefore the generators produced a smaller voltage operating into the tube than in their preliminary test.

After extremely careful and accurate adjustments of the tube we were able to feed to it for short periods (several seconds) a voltage of the order of 1,500,000 v; but we attained steady operation of the tube only at a voltage of about 1,100,000 to 1,200,000 v. (Note: We measured the voltage applied to the tube not only with the help of generating voltmeters, but also through the deflection of the electrons and ions accelerated in the tube by a magnetic field).

6. CERTAIN EXPERIMENTS PERFORMED WITH THE DISCHARGE TUBE

In the first experiments conducted with the discharge tube we accelerated electrons. The electron source was an incandescent cathode fed by batteries placed in the conductor of the generator. Judging from the glow of the fluorescent coating on the glass enclosing the opening in the lid that covered the opposite end of the tube, the electron beam was extremely diffused (the screen, 60 mm in diameter, glowed almost uniformly over its whole surface). Some rays concentrated in a beam were successfully obtained by moving the cathode 20-30 cm inside the tube; at the same time, however, the independent discharge in the tube appeared at noticeably lower voltages than when the cathode is placed inside the conductor. Isolating the electron beam with the help of a diaphragm 2 mm in diameter, we determined the energy of the electrons from the deflection of their beam by a magnetic field; this energy (depending on the system of operation of the tube) ranged from one to one and one half million volts. By releasing the electron beam through the aluminum window (0.05 mm aluminum foil glued to porous brass disk), we made it possible to measure their passage through different substances. The total current in the beam which was released through the window was from 0.1 to $1.0 \cdot 10^{-6}$ amp. By retarding the electron beam with a lead disk, we obtained x-rays which, though filtered by two centimeters of lead, produced noticeable blackening of a photographic plate when exposed for five minutes.

For experiments with lithium ions, the preliminary results of which have been published in a separate note (Sow Phys, 8, 212, 1935), the incandescent cathode was replaced by a platinum cylinder coated with spodumene (a mineral containing lithium which emits lithium ions on being heated).

Finally, we conducted a series of preliminary experiments with protons on this tube. The proton source was a Cockcroft-Walton channel tube which was connected to the outlet in the lid of the main discharge tube. The diagram of this tube together with its feeding apparatus, which was placed inside the conductor of the electrostatic generator, is shown in Figure 5, and a photograph in Figure 6.

The hydrogen was inserted through a palladium tube with a sealed end and was regulated by the variation of the oven surrounding it. The apparatus for feeding the channel tube consisted of an alternator driven by a motor mounted on the floor, a high-voltage transformer (110/18,000 v_{eff}), and a mechanical rectifier. Under correctly matched conditions for discharge in the channel tube, the beam of protons passing through the large discharge tube is quite sharply focused (the spot's diameter was less than one centimeter), but the spot's position on the screen was unstable: the spot moved in an irregular manner within the limits of 2-3 cm from the axis of the tube.

In spite of many attempts, we have not yet succeeded in stabilizing the spot's position. With the purpose of investigating the scattering of protons by protons due to collisions, we introduced the proton beam through a window about 0.1 mm in diameter, covered with mica about 2 μ thick, into a Wilson cloud chamber filled with hydrogen. (Note: The chamber constructed by us was 10 cm in diameter and did not differ essentially in its construction from the chamber with a rubber membrane described by Wilson (Proc Roy Soc (A), 142, 88, 1933)). [redacted] (see Figure 7, which shows a photograph of the interior of the conductor with the Wilson chamber attached to the discharge tube). The numerous visual observations which we made of the tracks (which were ~~obtained~~ quite distinct and in sufficient numbers) showed that large angular deflections are encountered so rarely that observation of them with the aid of a Wilson chamber is in practice not feasible. We will continue such experiments in other apparatus.

This short summary already has shown clearly that the types of generators developed by us have proved the worth of employing this kind of voltage source in experiments with discharge tubes at voltages higher than one million volts; however, the generators described did not satisfy us, for they possessed comparatively little power in spite of their large size. However we developed an improved type of generator, which will be described below.

7. GENERATORS WITH SPHERICAL CONDUCTORS

(Note: A number of design features used by us in the building of this generator were borrowed from the work of Bramhall (Rev Sci Instr, 5, 18, 1934).

The diagram of the generator is shown in Figure 8, and its external appearance is pictured in Figure 9. The basic elements of its design are: split spherical conductor A pressed from sheet copper 1.5 mm thick; insulator structure in the form of an insulating cylinder B 350 mm in diameter and 1000 mm long with a wall 5 mm thick; and rollers C,D,E,F, rotating on ball-bearings and with their axles mounted in welded frames. The rollers were cast of aluminum and were accurately balanced before being mounted in the generator. Balloon cloth (rubberized two-ply percale) was successfully used for the belt, which in this type of generator works under more difficult conditions since it is subjected to reversed bending. The maximum voltage obtainable from the generator when operating "at no load" is a little more than 700 kv (measured with the help of discharge spheres 720 mm in diameter). At the farthest separation of the dischargers, the discharge proceeds from the conductor to the welded casing G of the generator. The belt is set in motion by a 250-watt three-phase induction motor M, mounted on the platform H, which is, in turn, hinged to the welded casing of the generator. The maximum belt velocity which we succeeded in obtaining on this generator was 33 meters per second. Normally generators of this type operate at a belt velocity of 25 meters per second. Under these conditions the generator possesses the external characteristic pictured in Figure 10, in which the current taken from the generator was plotted along the abscissa. (Note: The characteristics were taken by draining off the corona point, at different distances from the conductor, through a galvanometer to ground). The potential of the conductor was plotted along the ordinate. The belt is charged from an auxiliary high-voltage device at 20 kv. The generator can also operate without external excitation. In this case the charging devices are connected together as in Figure 11. However, we did not succeed in obtaining from the generator more than 50% of the current produced by it in independent operation. Moreover, when self-excited the generator operates much less stably and is very sensitive to moisture in the room, and the sign of its charge changes from one starting to the next. All this forced us to utilize the auxiliary charging device in all the generators of the described type.

8. WAYS FOR THE FURTHER DEVELOPMENT OF THE GENERATORS

Further development of the generators can proceed in several directions. On the one hand, keeping the basic constructional features of the generator one can increase its linear dimensions. Since the power of the generator increases approximately in proportion to the cube of the linear dimensions (voltage is proportional to the dimensions of the conductor and current is proportional to the area of the opening in the conductor). On this principle we constructed the large generator described in section 2. On the other hand, keeping the same dimensions for the generator one can increase considerably the current produced by it by replacing the atmosphere in which the belt moves by a medium with a greater dielectric strength (compressed gas) and with a larger dielectric constant (insulating liquid). Proceeding in this way we can expect to increase the generator's power in proportion to the product of dielectric constant and dielectric strength of the medium surrounding the belt.

At present we are constructing a generator filled inside with transformer oil; experiments with this will permit us to varify the accuracy of the above considerations.

Another possibility is to attempt to raise the generator's voltage by surrounding its conductor with a solid, liquid, or gaseous dielectric of high dielectric strength. We are also conducting experiments of this type.

Finally, one can try to find a solution by a new design that rejects the belt construction. In particular, one of the possible solutions to the problem is the replacement of the belt by charged dust driven along by a rapidly moving stream of air. We are conducting preliminary experiments in this direction also.

In the construction of the different generators and tubes, and in the experiments much assistance was afforded us by our co-workers Engineer Vermel' (construction and testing of the generator with the spherical conductor), Engineer Taranov (construction and testing of the tube), Engineer Vodolazhskiy and Engineer Marushchak, to whom we express our gratitude.

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