VACUUM ELECTROSTATIC ENGINEERING

By

John G. Trump

E. E. Polytechnic Institute of Brooklyn, 1929.
M. A. Columbia University, 1931.

Submitted in partial fulfillment of the
requirement for the degree of

Doctor of Science

from the

Massachusetts Institute of Technology

1933

Signature of Author ....
Certification by Department ....

Read Dec. 1933
V. Bush
read Oct. 1934
E. A. Guillemin

ACKNOWLEDGMENT

It is a pleasure to recall the stimulating and invaluable association during this research with Dr. Robert J. Van de Graaff. It was his experimental work and vision which started vacuum electrostatic engineering, and during this investigation he has contributed unfailingly of research technique, ideas, and inspiration.

TABLE OF CONTENTS

CHAPTER I

VACUUM ELECTROSTATIC ENGINEERING

This report describes an investigation of the electrical engineering possibilities of machines depending on electrostatic forces and principles and utilizing high vacuum as the essential insulating medium. This combination of electrostatic devices and vacuum insulation makes possible, it is believed, a new type of power system - capable of all the functions of modern power systems, but possessing unusual ultimate advantages in power capacity, overall efficiency, distance of transmission, reliability, and economy.* The various elements of such a complete vacuum electrostatic power system are discussed in succeeding chapters of this report. The basic characteristics of vacuum insulation and of electrostatic power machinery which, in combination, open up this new and tremendously important field in power engineering are discussed immediately below.

A. HIGH VACUUM INSULATION

High vacuum is believed to be the ultimate insulating medium for high-power and high-voltage electrical-engineering applications. This belief in the ultimate superiority of high-vacuum insulation is based on the following fundamental considerations:

---

* The conception of a vacuum-electrostatic power system, its possibilities and practical means of realization were briefly described in a "Report on Present and Proposed Research" presented to President K. T. Compton of M.I.T. on March 20, 1931, by R. J. Van de Graaff, then at Princeton. A paper entitled, "Electrical Engineering Possibilities of Electrostatics with Vacuum Insulation" was presented by invitation before the annual meeting of the British Association at Leicester on September 12, 1933, by R. J. Van de Graaff.

(1) By far the highest voltage gradients (electrostatic forces) between metallic electrodes can be maintained in high vacuum. In a sufficiently high vacuum the voltage gradients that can be maintained depend principally on the nature and preparation of the electrode surfaces. Hayden[1] reports a maximum gradient at the cathode surface of 1.3×10^6 volts per centimeter between outgassed molybdenum spheres. Piersol[2] claims a cathode gradient of 5.4×10^6 volts per centimeter between molybdenum plates outgassed at 1400 degrees C. R. J. Van de Graaff, in an experiment performed at Princeton in 1931 obtained indications of a cathode gradient of 5.5×10^6 volts per centimeter between small metallic spheres, the cathode sphere being covered with a thin film of pyrex. Experiments performed during this investigation using sphere gaps made of 1/2" polished steel balls, unoutgassed, indicated that cathode gradients of the order of 1×10^6 can be consistently obtained under these conditions. A more detailed account of these gradient studies is contained in Chapter VI.

While the possibility of attaining in vacuum voltage gradients at the negative electrode as high as those indicated above has not generally been known to the art,[3] the fact that voltage gradients of tens of millions of volts could be maintained at the positive electrode has been generally recognized. Advantage can be taken of these gradient differences, particularly when extremely high voltages are involved, by so geometrically disposing the cathode surface relative to the anode surface that the field is distributed (weak) over the cathode surface

---

[1] Hayden, Jour. A.I.E.E., 41, p. 854, 1922.

[2] Piersol, Report of British A.A.S., p. 359, 1924.

[3] (Particularly in the coated-cathode and the unoutgassed electrode cases.)

and concentrated (strong) over the anode surface. A practical application of this conception[1] is a vacuum transmission line consisting of a relatively small rod serving as the positive conductor or anode, which runs axially through a cylindrical shell serving as the return conductor, the space between the two being evacuated.

The electrostatic force acting on electrodes varies as the square of the voltage gradient at their surface. The rapidity with which the magnitudes of these forces increase with gradient is illustrated by the following example: The electrostatic force between two parallel plates 10 ins. square (neglecting edge effects) due to a voltage gradient of 300 volts per centimeter is about 0.00006 lb.; for a voltage gradient of 30,000 volts per centimeter (which is about the limit for electrodes in air) the force is a little over one-half pound; for a gradient of 3,000,000 it would be over 5,700 lbs. These tremendous forces, which can be produced only in vacuum, are herein claimed and shown to offer possibilities of extreme importance in the field of electrostatic power machinery and engineering.

The insulation of extremely high voltages can be best accomplished in high vacuum. Voltages of almost a million volts have already been insulated in vacuum under disadvantageous conditions and there is sound theoretical reason for the belief that many millions of volts can be safely and practicably insulated in vacuum.[2] In air it is impracticable to insulate steady voltages greater than 10 million,

---

[1] First suggested by R. J. Van de Graaff and investigated as part of this research.

[2] One phase of the activities of Dr. R. J. Van de Graaff is directed toward the realization of a d-c. generator in vacuum for nuclear experiments capable of developing voltages measured in tens of millions.

a sphere 15 ft. in diameter and suitably insulated from ground being required to hold such a voltage.*

(2) A vacuum offers no resistance to moving parts. This property of a vacuum is advantageous in two distinct ways: (a) It eliminates completely the energy loss (windage or its equivalent due to viscosity) inevitably accompanying the operation of dynamic machinery in all other media. (b) It permits the making and breaking of electrical connections by actual physical contact or separation of electrodes without any accompanying decomposition of the surrounding insulating media (as would be the case in general with material insulation such as oil, etc.) and without any physical opposition to such movement.

(3) A high vacuum can, by simple and easily controlled means, be rendered an excellent unidirectional conductor of electricity, and can from this condition at will be restored to its former highly insulating state; an important feature of this unique property is that these transitions can be accomplished with only a minute expenditure of controlling energy, in less than a millionth of a second, and without changing necessarily the potential between the two terminating electrodes. This conception has important practical applications, as is illustrated by the various direct- and alternating-current switches described in Chapter VII of this report.

(4) An insulating high vacuum cannot of itself support space charge unless the charge is artificially introduced, as for example, by thermionic emission.

---

* These are the rated voltage and physical dimensions of the Van de Graaff high-voltage generator at Round Hill, Mass.

(5) A high vacuum has no dielectric hysteresis loss.

(6) A high vacuum of itself has no surface or volume leakage.

(7) An important property of high vacuum as an insulating medium is its ability to pervade, in a very complete sense and with absolute homogeneity, the interelectrode space. This ability eliminates the costs, difficulties, and imperfections accompanying the forming or impregnating operations required with material insulators.

(8) Vacuum insulation is self-healing.

(9) Vacuum is unaffected by temperature changes. This consideration eliminates the important operating temperature limitations of material insulators.

(10) Vacuum is incapable of transmitting sound. This quality has important advantages in the reduction of the noise accompanying the operation of power machinery.

(11) Vacuum suffers no change or deterioration of insulating properties with time. Such deterioration is commonly experienced in varying degrees by material insulators such as paper, rubber, fiber, oil, etc.

(12) Vacuum is incombustible and acts as an effective preventive of combustion. It reduces fire hazard, whereas the use of hydrogen, paper, rubber, oil, etc. increases this hazard.

(13) Vacuum insulation would in practice to a large extent eliminate all danger to human life commonly accompanying the presence of high-voltage power. This comparative safety is the result of the necessity of enclosing all high-voltage parts in a vacuum-tight container which would be of metal and at earth potential and hence would completely shield all external objects both from voltage and from

accidental arcs.

(14) Vacuum is transparent. This property enables the close observation of the mechanical motion and general state of the material objects contained therein, removing to a large extent the obscurities caused by other insulation processes such as immersion in oil, or the shielding or binding with relatively opaque insulating materials. It further permits the use of light or of devices depending on the transmission of light, for the control of mechanisms or machines operating in the vacuum or for the transmission of intelligence between it and the external region.

(15) Vacuum insulation to a large degree eliminates the necessity and therefore the cost of material insulators. A recently-constructed three-phase, 250,000-volt, 8000-ampere oil circuit breaker requires 66,000 gallons, or over 230 tons, of costly high-grade insulating oil.

(16) Vacuum is without weight. The importance of this lies in the elimination of the necessity and expense of supporting the weight of material insulation, whether in storage, operating position, or shipment.

(17) Vacuum insulation permits, without sacrifice in reliability, a very close and rapid practical realization of its optimum theoretical possibilities in machine design. In contrast to this, the use of material insulators must be accompanied by large factors of safety and much experimentation to take care of the obscurities and uncertainties caused by space charge, leakage, variability from sample to sample, deterioration, etc.

It is evident that these advantageous and often unique properties of high vacuum as a voltage insulating medium render it far superior to any material insulator now known to the electrical art. High vacuum, being in practical effect the absence of all matter, is free from the inevitable limitations and imperfections of material substances. These considerations form in part the basis of our belief that high vacuum is the ultimate insulating medium and, as such, will characterize and extend in an unprecedented way the electrical engineering of the future.

The practical realization of the unusual electrical insulating properties of high vacuum is attended by certain special problems, some of which will now be briefly discussed.

(1) Vacuum is incapable of supporting the physical structure which it insulates. Hence, in general, material insulators must be used in vacuum to perform this function. The relative amount of this material insulation, however, is small and can usually by proper design be located in regions of low electric stress. In this way full and effective use of the properties of vacuum insulation can still be made. It is moreover possible to produce for the special purpose of supporting high-potential bodies in vacuum, material insulators many times more compact than the equivalent insulators now available for use in other media. These and other aspects of the problem of material insulation in vacuua are discussed in detail in Chapter VI.

(2) The electrical insulating properties of high vacuum are dependent upon the surface conditions and the characteristics of the electrodes therein. Discriminating choice of electrode material and

the proper electrode design and treatment are essential to the practical realization of the vacuum insulation characteristics disclosed above. It will be seen in Chapter VI where this problem is more fully discussed, that in the limit it is still the imperfections of the material electrodes that fix the insulating properties of high vacuum.

(3) "Nature abhors a vacuum." This unphilosophical doctrine, maintained by philosophers for 2000 years, grew out of the ancient recognition of the difficulty of producing and maintaining even a poorly evacuated condition. The problem of producing and maintaining in a reliable engineering manner, within a large metal tank, an evacuated condition many million times improved over that suggested above, and yet so intimately linked with the outside world that power and control can easily be transmitted between them, is correspondingly greater. By contributing to contemporary vacuum technique certain new ideas which make for engineering usefulness and reliability, the way toward a practical solution of this problem has been disclosed and experimentally demonstrated during this investigation. This work on vacuum technique is described more fully in Chapter V.

B. VACUUM ELECTROSTATIC VERSUS ELECTROMAGNETIC MACHINERY

It is believed that machines operating on electrostatic principles utilize more advantageously the unique insulating properties of high vacuum than electromagnetic machines. Vacuum electrostatic machines for energy conversion and transformation purposes have therefore been subjected to considerable analysis and development during this investigation. In general, devices based on electrostatic forces and principles have certain fundamental and important advantages over devices depending on electromagnetic forces and principles. Among these are the following:

(1) The maintenance of appreciable electromagnetic fields and forces requires the continuous movement of large quantities of electricity and therefore continuous power loss, whereas for the maintenance of electrostatic fields and forces only the presence and not the motion of electricity is required. Hence electrostatic forces can be maintained with no power loss. In electrostatic machines the power loss due to charging current takes place only during the charging intervals and may be made small by the use of high voltages; in electromagnetic machines the power loss for the same current density takes place continuously and cannot be avoided by increase of operating voltage. These considerations indicate that electrostatic processes are inherently more efficient than corresponding electromagnetic processes.

(2) The maintenance of an electrostatic force is, in its nature, a direct and primary manifestation, while the maintenance of an electromagnetic force (force on a conductor carrying a current in a transverse magnetic field) is by nature a complex and secondary manifestation; these facts are reflected in that electrostatic machines can in general be made simple as well as efficient, while electromagnetic machines remain relatively more complex and inefficient. By electromagnetic machines are meant all energy-converting or transforming devices involving as a predominant characteristic the interaction of magnetic fields. By electrostatic machines are meant all energy-converting or transforming devices involving the use of electric forces as the predominant characteristic without the necessary use of magnetic forces.

(3) Electromagnetic machines require per unit power fairly definite volumes of heavy material such as iron and copper, since these materials have practical limitations in the flux density and current density, respectively, to which they can be subjected. These limitations of the materials essential to electromagnetic machinery put on this class of apparatus a weight and size per unit power restriction. This restriction is not present in vacuum electrostatic machinery since in general the electric force between electrodes is independent of the volume of the electrode and of the material below the surface. This fact, coupled with the high energy concentrations of which high vacuum as dielectric is capable, leads to the conclusion that as far as ultimate limitations are concerned, electrostatic machines have the advantage of lightness and compactness over electromagnetic machines.

The above basic considerations indicate that, in their ultimate forms, vacuum electrostatic power machinery will exhibit advantages over electromagnetic machinery in greater efficiency, simplicity, lightness, and compactness. The following practical considerations should also be cited:

(a) In addition to the higher efficiency inherent in the electrostatic processes themselves, the absence of dielectric loss (except for the small amount associated with the material insulators supporting the electrodes), the complete absence of magnetic loss, the large reduction of the charging current heat loss (through the use of the high voltages possible in vacuum and because of the low-resistance construction which characterizes the proposed electrostatic power machinery), and the complete elimination of windage loss, - all these result in a total power loss for electrostatic machines which is many times less than the loss in equivalent electromagnetic machines.

(b) The all-metal construction of the electrodes of the electrostatic power machinery proposed herein, and the generally necessary use in vacuum of material insulation which is non-organic, removes to a large extent from vacuum electrostatic machines the temperature rise limitation which is common to all electromagnetic machines. This freedom from a narrowly-restricted permissible temperature rise, together with the low losses inherent in high-voltage vacuum electrostatic processes, makes possible for the first time electrical machinery whose power capacity is limited by its electrical and mechanical ability to develop power, and not by its ability to dissipate the energy loss involved in the process.

C. ELECTRICAL ENGINEERING APPLICATIONS OF VACUUM ELECTROSTATICS

The major portion of this research was devoted to the practical application of vacuum electrostatics to electrical power engineering. This phase of the research proceeded along several paths; it involved the development and analysis of new types of electrostatic power machinery, the development and study of the other elements of a complete power-transmission system such as d-c. power transmission and switching, the study of practical details of design, estimates of costs, and comparison with existing power systems. It involved also the experimental study of model power electrostatic machines, the development of engineering vacuum technique, and the test of vacuum and material insulation strength.

This work is described in the following chapters and has shown the practicability of the following applications of vacuum electrostatics to electrical power engineering:

(1) Machines operating on electrostatic principles and in high vacuum can be developed to perform all those energy-conversion functions now regularly performed by high-power electromagnetic or electronic machinery such as motors, generators, transformers, converters, rectifiers, inverters, etc.

(2) Machines operating on electrostatic principles and in high vacuum can be developed for the direct generation and direct conversion of high-voltage direct-current power - a function not as yet practicable by present electromagnetic or electronic devices.

(3) Such large-power electrostatic machines operating in high vacuum can be developed for a range of voltages of the order of 50,000 to several millions of volts.

(4) Such vacuum electrostatic machines would have power losses many times less than those of corresponding rotating electromagnetic machines; these losses would be of the order of one per cent.

(5) Such machines would be capable of more power per unit weight or per unit size than is now developed by modern electromagnetic machinery.

(6) Such electrostatic machinery would be essentially a simple variable condenser or combinations of such variable condensers with suitable switching and circuit arrangements.

(7) Both rotor and stator of such machines might be of metal, though not limited to metal or conducting material. For machines with metallic rotor and stator, the amount of required insulation material,

other than the high vacuum itself, would be made relatively small and located away from the active electric fields.

(8) The probable best type of high-power electrostatic machine would be of the interleaving parallel plate type or variations of this type.

(9) Transmission lines can be developed to transmit practically unlimited amounts of d-c. power over practically unlimited distances at voltages of the order of millions of volts and at extremely high efficiencies. The essential feature of such a transmission line is a central positive conductor running axially through a highly-evacuated metal tube constituting the cathode or return conductor. It is recognized also that for intermediate voltages of the order of one million volts, d-c. power cables of the conventional type may be used as the transmitting link of the electrostatic power system.

(10) High vacuum electronic switches can be developed capable of conducting, with high efficiency, the currents involved in such high-voltage direct-current high-power systems, and capable of interrupting these currents and withstanding the full line voltage. Electronic switches can be developed to perform the commutating functions in high-voltage vacuum electrostatic power machinery.

(11) Such a high-voltage vacuum transmission line might terminate in suitable high-voltage vacuum electrostatic machinery and thus, with this terminal equipment and with the electronic switches and auxiliaries, constitute a complete power system capable of all the functions of modern power transmission systems, but transmitting direct-current power at voltages of a million or more volts and with an over-all

efficiency for substantially unlimited distances (through generation, transmission, and conversion), departing from 100 per cent by an amount of the order of 4 per cent.

(12) Such a vacuum electrostatic power system is capable of rapid realization and, in its ultimate form, besides offering great advantages over present electromagnetic systems in power capacity, efficiency, and range of transmission, is inherently capable of great reliability and lower cost.

CHAPTER II

VACUUM ELECTROSTATIC MACHINE ANALYSIS

Various types of vacuum electrostatic machinery - alternating-current generators and motors, direct-current generators and motors, etc. - were developed and analyzed during this investigation. In this chapter the more important of these are described, their operating principles and characteristics disclosed, and many of the functional and design problems and their solutions indicated. This chapter covers only vacuum-electrostatic-machinery analysis and does not cover problems of vacuum technique or vacuum and material insulation characteristics, which are discussed later. All of the machines herein described are believed to be capable of practical application in a high-voltage power system exceeding in power capacity, efficiency, and range of transmission, any electric power system now existent.

A. ALTERNATING-CURRENT SYNCHRONOUS ELECTROSTATIC MACHINE - TYPE 1 *

The machine is essentially a variable condenser which may be of the parallel-plate interleaving type, as shown in Fig. 1. For operation as a motor a suitable source of high-voltage a-c. power is impressed across rotor and stator. In practice, one of these members, preferably the rotor, may be grounded.

1. Principle of Operation

The general equation for the current flowing at any instant in a condenser circuit whose capacitance and impressed voltage vary

---

* First described by Dr. R. J. Van de Graaff.

with time is

$$i = C\frac{de}{dt} + e\frac{dC}{dt} \tag{1}$$

The power input to the circuit at any instant is found by multiplying Equation (1) by e:

$$p = ie = Ce\frac{de}{dt} + e^2\frac{dC}{dt} \tag{2}$$

The first term in the right-hand number of Equation (2) does not involve any transformation of electrical to mechanical power. It represents the power transfer between the outer circuit and the electrostatic field due to change in voltage.

The second term contains within it the transformation from electrical to mechanical power. The mechanical power is equal to one-half the value of the second term, that is,

$$p = \frac{e^2}{2}\frac{dC}{dt} \tag{3}$$

and represents the rate at which work must be done on or by the system at voltage <u>e</u> to cause its capacitance to change at the rate dC/dt. The remaining half represents the rate at which the stored electrostatic energy in the system at voltage <u>e</u> is changing due to the capacitance variation dC/dt. If dC/dt is positive, then electrical energy is being absorbed by the circuit and mechanical energy is being delivered. If dC/dt is negative, then mechanical energy is being absorbed and electrical energy delivered.

Equations (1), (2), and (3), or their equivalents, are the basis of studies of electrostatic machines. From Equation (2) it is seen that for an alternating-current electrostatic machine consisting of a simple variable condenser upon which a periodic voltage e is impressed, to develop power as a motor, dC/dt must be positive when e is large, and negative when e is small. Such a motor will run at a synchronous speed given by

$$n = 120 \frac{f}{p} \text{ revolutions per minute} \tag{4}$$

where f is the frequency of the impressed voltage in cycles per second and p is the number of poles or the number of cycles of capacitance variation per revolution. Such a motor will adjust itself to increasing loads by changing its "power angle" in a manner analogous to that of the well-known electromagnetic synchronous motor. When the maximum power angle is reached, further increase in load causes the motor to pull out of step.

For such a machine to develop power as a generator, dC/dt must be negative when e is large, and positive when e is small. For a given periodic voltage e, the synchronous speed is again given by Equation (4) and the electric power delivered to the line is again a function of the power angle.

The time rate of capacitance variation of these electrostatic machines at constant synchronous speed may be a rectangular wave of double frequency (relative to the line voltage frequency), or a sinusoidal wave of double frequency, or any periodic curve having as an essential component a sinusoid of double frequency.

2. Capacitance Variation and Power

The purpose of this analysis is to determine the kind of capacitance variation which will produce maximum power capacity in an electrostatic synchronous machine with given size of disks.

$$\text{Let} \quad e = E \sin(\omega t + \theta) \tag{5}$$

and

$$C = C_o - C_1 \cos \omega t - C_2 \cos 2\omega t \ldots\ldots - C_n \cos n\omega t \tag{6}$$

This is the Fourier series expression for the most general kind of capacitance time-variation. Then

$$\frac{dC}{dt} = C_1\omega \sin \omega t + 2C_2\omega \sin 2\omega t + \ldots\ldots + nC_n\omega \sin n\omega t \tag{7}$$

From Equations (3), (5), and (6) the average power is

$$P_a = \frac{E^2\omega}{4\,\pi}\int_o^{\frac{2\pi}{\omega}} \sin^2(\omega t+\theta)\left\{C_1\omega \sin \omega t + 2C_2\omega \sin 2\omega t + \ldots\ldots + nC_n\omega \sin n\omega t\right\}dt$$

$$= \frac{E^2\omega}{4\pi}\int_o^{\frac{2\pi}{\omega}} \frac{1-\cos 2(\omega t+\theta)}{2}\left\{C_1\omega \sin \omega t + 2C_2\omega \sin 2\omega t + \ldots\ldots + nC_n\omega \sin n\omega t\right\}dt \tag{7a}$$

All the terms except the second in the bracket of Equation (7a) drop out. Hence

$$P_a = \frac{E^2\omega C_2}{4} \sin 2\,\theta. \tag{8}$$

It is evident from this that, with sinusoidally-varying voltage, only the double-frequency sinusoidal component of the total capacitance time-variation (or of the time rate of capacitance change) contributes to the power.

Two different time rates of capacitance change will now be examined. The first will be a double-frequency rate of capacitance change of rectangular wave shape, and the second a double-frequency rate of capacitance change of sinusoidal wave shape.

The Fourier series for the time rate of capacitance change of rectangular wave shape and unit amplitude, illustrated in Fig. 3, is:

$$\frac{dC}{dt} = \frac{4}{\pi}\left(\cos 2\omega t - \frac{1}{3}\cos 6\omega t + \frac{1}{5}\cos 10\omega t + \ldots\ldots\right) \qquad (9)$$

It is only the first term of this series, as has been proved above, that contributes to the power. If the maximum change of capacitance in a machine with uniform capacitance variation and given size of disk be C_m then the amplitude of the corresponding rectangular-waved rate of change of capacitance is

$$\text{Amplitude} = \frac{2\omega C_m}{\pi} \qquad (10)$$

and the equation of the power-producing fundamental of this is by (9):

$$\frac{dC}{dt} = \frac{8\omega}{\pi^2} C_m \sin 2\omega t \qquad (11)$$

It is shown in Appendix A that if disks of this same given size were shaped so as to secure a sinusoidal rate of change of capacitance, the maximum change of capacitance would be only $2/\pi\ C_m$. The time rate of change of capacitance in this case is therefore

$$\frac{dC}{dt} = \frac{d}{dt}\left(\frac{2}{\pi} C_m \sin^2 \omega t\right) = \frac{2\omega}{\pi} C_m \cos 2\omega t \qquad (12)$$

Evidently then, since all other conditions are the same, the ratio of power developed by a machine with disks shaped for a sinusoidal time rate of change of capacitance to that developed by one of the same-sized disks, but designed for a rectangular time rate of change, is given by

$$\frac{\text{Eq. (12)}}{\text{Eq. (11)}} = \frac{\pi}{4} = 78.5 \text{ per cent} \qquad (13)$$

3. Power when Rate of Capacitance Variation is a Rectangular Wave

The rate of capacitance variation is a rectangular wave when the rotor and stator poles are sector-shaped, that is, when the capacitance varies uniformly with angle. Referring to Fig. 1, the maximum capacitance change between rotor and stator in vacuum during a cycle is closely given by:

$$C = 0.0884 \; 10^{-12} \frac{\pi(r_1^2 - r_2^2)2s}{2d} \text{ farads} \tag{14}$$

where

s is the number of rotor disks
d is the separation rotor to stator in centimeters

The time rate of change of capacitance is given by

$$\frac{dC}{dt} = \pm \frac{2npC}{60} = \frac{2np \; 0.0884 \; 10^{-12}}{60} \; \frac{\pi(r_1^2 - r_2^2)2s}{2d} \; \frac{\text{farads}}{\text{second}} \tag{15}$$

From Equation (3), for an impressed voltage given by $e = E \sin \omega t$, the instantaneous mechanical power developed by the machine is

$$p = \pm \frac{E^2}{2} \frac{dC}{dt} \sin^2 \omega t \tag{16}$$

The power, as shown in Fig. 2, is pulsating. There are successive intervals of motor and generator action during the cycle, the relative amounts of motor and generator power depending on the phase angle θ - the angle in electrical degrees between zero voltage and minimum capacitance. The average mechanical power is found by integrating over one-half cycle:

$$P_a = -\frac{E^2}{2} \frac{dC}{dt} \frac{1}{\pi} \left[\int_0^{\theta} \sin \omega t \, d(\omega t) - \int_{\theta}^{\theta + \frac{\pi}{2}} \sin^2 \omega t \, d(\omega t) + \int_{\theta + \frac{\pi}{2}}^{\pi} \sin^2 \omega t \, d(\omega t) \right] \tag{17}$$

$$= \frac{E^2}{2} \frac{dC}{dt} \frac{\sin 2\theta}{\pi}$$

$$= 14.7 \frac{10^{-16} nps}{d} (r_1^2 - r_2^2) E^2 \sin^2 2\theta \text{ watts} \tag{18}$$

$$= 17.6 \frac{10^{-16} fs}{d} (r_1^2 - r_2^2) E^2 \sin^2 2\theta \text{ watts} \tag{19}$$

4. Power with Sinusoidal Rate of Capacitance Variation

The rate of capacitance variation is sinusoidal when the capacitance variation itself (considering the minimum capacitance as zero) is of the form

$$C = C_m \sin^2 \omega t = \frac{C_m}{2} \ (1-\cos 2\omega t) \qquad (20)$$

The line voltage is again taken as

$$e = E \sin(\omega t + \theta) \qquad (5)$$

and the current from Equation (1) is

$$i = \frac{C_m E\omega}{2} \Big[\cos(\omega t+\theta) - \cos(\omega t+\theta)\cos 2\omega t + C_m E\omega \sin(\omega t+\theta)\sin 2\omega t\Big] \qquad (21)$$

The instantaneous power is

$$p = ei = \frac{C_m E^2 \omega}{2} \Big[\sin(\omega t+\theta)\cos(\omega t+\theta) - \sin(\omega t+\theta)\cos(\omega t+\theta)\cos 2\omega t + 2\sin^2(\omega t+\theta)\sin 2\omega t\Big] \qquad (22)$$

The average power is

$$P_a = \frac{C_m E^2 \omega^2}{4\pi} \int_0^{\frac{2\pi}{\omega}} \Big[\,''\,\Big] \, dt = \frac{C_m E^2 \omega^2}{4\pi} \Big[0 - \frac{\pi \sin 2}{2\omega} + \frac{\pi \sin 2}{\omega}\Big]$$

$$= \frac{C_m E^2 \omega}{8} \sin 2\theta \qquad (23)$$

Motor action is developed by this machine for power angles of $\theta = 0$ to $\pi/4$. Generator action is developed for $\theta = 0$ to $-\pi/4$.

The power developed by this machine in terms of its physical dimensions is

$$P_a = \frac{E^2 \sin 2\theta}{8} \ \frac{2\pi p n}{120} \ \frac{K \ 0.0884 \times 10^{-12} \pi (r_1^2 - r_2^2) 2s}{2d}$$

$$= \frac{1.815 \times 10^{-15} \ E^2 p n s (r_1^2 - r_2^2) k \sin 2\theta}{d} \ \text{watts} \qquad (24)$$

$$= \frac{218 \times 10^{-15}\, E^2 f s (r_1^2 - r_2^2) k \sin 2\theta}{d} \tag{25}$$

where

$K = \frac{2}{\pi}$

n = revolutions per minute

p = number of poles

s = number of rotor disks

f = frequency cycles per second

5. Effect of Parasite Capacitance on Current and Power Factor

In the foregoing analysis it was seen that the constant minimum capacitance C_o, upon which the varying capacitance was considered superimposed, had no effect on the average power. The effect of this minimum capacitance between rotor and stator on the line current and power factor will now be examined. The capacitance expression is more accurately given by

$$c = C_m(\sin^2 \omega t + \lambda) \tag{26}$$

where C_m is the maximum change of capacitance and λC_m is the minimum capacitance. Taking

$$e = E \sin(\omega t + \theta) \tag{5}$$

the current, from Equation (1), is given by

$$i = C_m(\sin^2 \omega t + \lambda)\omega E \cos(\omega t + \theta) + E \sin(\omega t + \theta)\omega C_m \sin 2\omega t$$

which reduces to

$$i = -\omega E C_m \left[A \sin(\omega t - \phi) + 3/4 \cos(3\omega t + \theta) \right] \tag{27}$$

where

$$A = \sqrt{(\tfrac{3}{4} + \lambda)^2 \cos^2\theta + (\tfrac{1}{4} + \lambda)^2 \sin^2\theta} \tag{28}$$

and

$$\phi = \tan^{-1} \frac{(3/4 + \lambda)\cos\theta}{(1/4 + \lambda)\sin\theta} \tag{29}$$

The power factor is the cosine of the angle between the fundamental components of voltage and current, or

$$P.F = \cos(90-\phi+\theta) \qquad (30)$$

Fig. 4 shows the effect of the minimum capacitance C_0 on current and power factor for all values of θ and two values of λ. It is seen that increase in λ greatly increases the current and greatly reduces the power factor. For single-phase machines of this type the power factor is still only 0.454 even when λ is zero, a condition not attainable in practice. It must be remembered, however, that in the high-voltage machines contemplated by this research, power-factor considerations are not nearly so important as in the present electromagnetic machines.

6. Third-Harmonic Current

More important is the relatively large third-harmonic current which exists, as shown in Equation (27). The third-harmonic current is independent of both power angle and minimum capacitance. When $\lambda = 0$, the third harmonic is always somewhat larger than the fundamental, except at no-load, when they are equal. For other values of λ it is only the additional reactive component of the fundamental which makes it overshadow the third harmonic. It must be noted that, while many harmonics are present in machines with uniform capacitance variation, it is only the third harmonic which still remains when the machine is designed so that the rate of capacitance variation is sinusoidal. Since, as will be disclosed, even this third harmonic can be eliminated in three-phase machines, it is evident that the sinusoidal rate of capacitance variation offers advantages over the rectangular and other types.

7. Polyphase Synchronous Electrostatic Machines, Type 1

While the synchronous electrostatic machines described above were single-phase, it is recognized that polyphase machines operating on the same principles may be made of such single-phase units properly displaced in phase relative to one another. Some of the possible circuit connections for two-phase and three-phase machines are shown in Fig. 5. The power formulas developed for the single-phase machine now give the power per phase for the polyphase machine, all the terms in these formulas becoming phase quantities. It is evident, without further analysis, that polyphase operation results in a far more uniform torque characteristic than single-phase operation.

It has been shown that one of the inherent characteristics of the single-phase machine operating on sinusoidal voltage are the prominent current harmonics which accompany the fundamental. It has also been shown that by shaping the rotor or the stator plates so as to make the rate of capacitance variation sinusoidal, all but the third-harmonic current can be eliminated. In a three-phase machine fed by or feeding into a three-phase transformer with the neutral connected, the third harmonics in each phase flow out through the neutral. A tertiary delta winding on the transformer will supply this third harmonic, so that no third-harmonic current due to the electrostatic machine appears in the external circuit beyond the transformer. A circuit embodying this idea is shown in Fig. 6.

It is not possible to balance out the third-harmonic currents for all loads in a polyphase machine by displacing the rotors relative to one another, and keeping the stators in phase, nor is this believed to be a practical method of reducing them.

B. ALTERNATING-CURRENT ELECTROSTATIC MACHINES - TYPE II

These machines* consist essentially of two sets of stator members between which a direct-current excitation voltage is maintained, and two sets of rotor members whose capacitance with the stator members varies periodically, preferably so that dc/dt at constant speed is a sinusoidal function. A four-pole machine of this type is shown in Fig. 7. From its schematic diagram given in Fig. 8 the machine is seen to constitute a capacitance bridge, the four capacitances in the arms of the bridge varying periodically in a given manner, the excitation voltage being applied across two opposite points of the bridge and the alternating-current line being connected by slip rings to the other two oppositely-located points.

For motor action an alternating-current voltage is impressed via the slip rings across the rotor members, the frequency of this voltage and the number of rotor poles determining the synchronous speed according to Equation (4). For generator action the machine is driven at synchronous speed and the alternating-current power taken from the slip rings. The voltage and power of this machine as a generator, and its power as a motor, can be controlled by regulating the direct-current excitation voltage.

Polyphase machines of this type have been devised. A schematic diagram for one of the several connections for a three-phase machine is shown in Fig. 9.

1. Machine Analysis with Resistance Loading

For a machine designed for a sinusoidal rate of capacitance variation, when the rotor is in the axis of reference (as in Fig. 7,

---

* A single-phase generator of this type for use in air is described in "Elektrostatische Maschinen," by W. Petersen, 1907.

A over a, B over b), the capacitance relationships, neglecting the parasitic minimum capacitance C_o, are given by:

$$\begin{aligned} C_{a-A} &= C \cos^2 \frac{\omega t}{2} \\ C_{b-A} &= C \sin^2 \frac{\omega t}{2} \\ C_{b-B} &= C \cos^2 \frac{\omega t}{2} \\ C_{a-B} &= C \sin^2 \frac{\omega t}{2} \end{aligned} \tag{31}$$

where C is the maximum capacitance change between any stator and any rotor group. The angular velocity ω of the current or the voltage between slip rings is given by

$$\omega = \frac{\pi\ n\ p}{60} = 2\ \pi\ f \tag{32}$$

in which n is the revolutions per minute, p the number of rotor poles, and f the corresponding synchronous frequency.

The current which flows between the slip rings through resistance R is given by

$$i = i_1 + i_2$$

where

$$\begin{aligned} i_1 &= C_{a-A} \frac{d}{dt}\left(\frac{e-V}{2}\right) + \left(\frac{e-V}{2}\right)\frac{d}{dt}\ C_{a-A} \\ &= C \cos^2 \frac{\omega t}{2}\ \frac{d}{dt}\left(\frac{e-V}{2}\right) + \left(\frac{e-V}{2}\right)\frac{d}{dt}\ C \cos^2 \frac{\omega t}{2} \\ i_2 &= C_{A-b} \frac{d}{dt}\left(\frac{e+V}{2}\right) + \left(\frac{e+V}{2}\right)\frac{d}{dt}\ (C_{A-b}) \\ &= C \sin^2 \frac{\omega t}{2}\ \frac{d}{dt}\left(\frac{e+V}{2}\right) + \left(\frac{e+V}{2}\right)\frac{d}{dt}\ C \sin^2 \frac{\omega t}{2} \end{aligned}$$

Hence

$$i = \frac{C}{2}\left(\cos^2\frac{\omega t}{2} + \sin^2\frac{\omega t}{2}\right)\frac{de}{dt} + \frac{VC}{2}\ \frac{d}{dt}\left(2\sin^2\frac{\omega t}{2}\right)$$

$$= \frac{C}{2}\ \frac{de}{dt} + \frac{VC\omega}{2}\sin\omega t \tag{33}$$

and

$$e = \frac{CR}{2}\ \frac{de}{dt} + \frac{VCR\omega}{2}\sin\omega t \tag{34}$$

The solution of this differential equation is of the form

$$e = K\cos(\omega t-\phi) \tag{35}$$

The arbitrary constants are evaluated by putting Equation (35) and its time derivative into Equation (34) and solving for the boundary cases when $(\omega t-\phi) = 0$, and when $\omega t = 0$. Equation (35) then becomes

$$e = \frac{V}{\sqrt{1+\left(\frac{2}{CR\omega}\right)^2}}\cos(\omega t-\phi) \quad \text{where } \phi = \tan^{-1}\frac{2}{CR\omega} \tag{36}$$

Hence

$$i = \frac{e}{R} = \frac{V}{R\sqrt{1+\left(\frac{2}{CR\omega}\right)^2}}\cos(\omega t-\phi) \tag{37}$$

$$p = ei = \frac{V^2}{R+R\left(\frac{2}{CR\omega}\right)^2}\cos^2(\omega t-\phi) \tag{38}$$

$$P_a = \frac{V^2C^2R\omega^2}{2(C^2R^2\omega^2+4)} \tag{39}$$

and the power factor is unity.

The above analysis is for generator action. If voltage <u>e</u> is replaced by -e, which signifies an impressed voltage, or motor action, the same analysis and resultant relations hold except for the 180-degree change of phase between voltage and current.

2. Maximum Average Power

The relationship between R, C, and ω which results in maximum power from a machine of given size is found by writing

$$\frac{\partial P}{\partial R} = 0 \tag{40}$$

where P is given by 0. 3? It is found that the average power is maximum when

$$R = \frac{2}{C\omega} \tag{41}$$

Substitution of Equation (41) in Equations (39) and (36) gives, for maximum average power and corresponding alternating-current voltage,

$$P_{max} = \frac{V^2 C\omega}{8} \tag{42-a}$$

In terms of the physical constants of the actual machine this becomes

$$P_{max} = \frac{0.578 \times 10^{-15}\ nps(r_1^2 - r_2^2)V^2}{d} \tag{42-b}$$

$$e_{Pmax} = \frac{V}{\sqrt{2}} \cos(\omega t - \phi) \tag{43}$$

The effective alternating-current voltage in this case of maximum power is

$$E_{eff_{Pmax}} = \frac{V}{2} \tag{44}$$

3. No-Load

The no-load condition of the machine is described by

$$\frac{C}{2}\frac{de}{dt} + \frac{VC\omega}{2}\sin\omega t = 0 \tag{45}$$

The current between the slip rings is zero (corresponding to an infinite R) and the alternating-current voltage across them is again of the form given by Equation (35). On evaluating the arbitrary constants, this becomes

$$e_{n\ell} = V \cos \omega t \tag{46}$$

4. Voltage Regulation

The voltage regulation in this case of unity power factor is 41.5 per cent from no-load to maximum load.

The current i_f in the stator circuit at no-load, assuming constant inducing voltage V, is

$$i = i_1 - i_2 = -\frac{\omega CV}{2} \sin 2\omega t \tag{47}$$

5. Short Circuit

At short circuit e = 0 and short-circuit current between slip rings is given by

$$i = i_1 - i_2 = \frac{V}{2} \frac{d}{dt} C \cos^2 \frac{\omega t}{2} - \frac{V}{2} \frac{d}{dt} C \sin^2 \frac{\omega t}{2} = \frac{VC\omega}{2} \sin \omega t \tag{48}$$

The current i_f in the stator inducing circuit for constant V is

$$i_f = i_1 + i_2 = \frac{V}{2} \frac{d}{dt} C \cos \frac{\omega t}{2} - \frac{V}{2} \frac{d}{dt} C \sin^2 \frac{\omega t}{2} = 0 \tag{49}$$

6. Machine Analysis with Resistance and Inductive Loading

In this case, the external circuit connected to the slip ring has a resistance R and an inductance L. With this exception Fig. 7 still applies, and the equation for the current through the external circuit is still

$$i = \frac{C}{2} \frac{de}{dt} + \frac{VC\omega}{2} \sin \omega t \tag{33}$$

and

$$\frac{di}{dt} = \frac{C}{2}\ \frac{d^2e}{dt^2} + \frac{VC\omega^2}{2}\cos \omega T \qquad (50)$$

The voltage e across the external circuit is given by

$$e = Ri+L\frac{di}{dt} = \frac{LC}{2}\ \frac{d^2e}{dt^2} + \frac{LCV\omega^2}{2}\cos \omega t + \frac{RC}{2}\ \frac{de}{dt} + \frac{RVC\omega}{2}\sin \omega t \qquad (51)$$

The solution of this differential equation is again of the form

$$e = K\cos(\omega t-\phi) \qquad (35)$$

Evaluating the arbitrary constants by the same method as before gives

$$K = \frac{(R^2C\omega+L^2C\omega^3)V}{\sqrt{4R^2+(R^2C\omega+2L\ \omega+L^2C\omega^3)^2}} \qquad (52)$$

and

$$\phi = \tan^{-1}\frac{2R}{R^2C\omega+2L\ \omega+L^2C\omega^3} \qquad (53)$$

It is seen that Equation (35) with its constants defined by Equations (52) and (53) reduces to Equation (36) when L = 0.

Since the alternating current of the machine, if the voltage across the external circuit is known, is governed by the constants of the external circuit, we have

$$i = \frac{K}{\sqrt{R^2+\omega^2L^2}}\cos(\omega t-\phi-\theta) \qquad (54)$$

where K and ϕ are given by Equations (52) and (53), respectively, and

$$\cos\theta = \frac{R}{\sqrt{R^2+L^2\omega^2}} = \text{power factor.} \qquad (55)$$

7. Effect of the Parasite Capacitances, C_0.

The effect of the undesirable, though inevitable, constant minimum capacitances C_0, on which the varying capacitances C are superimposed, will now be considered. Equations (31) now become

$$\begin{aligned} C_{a-A} &= C(\cos^2 \frac{\omega t}{2} + \lambda) \\ C_{b-A} &= C(\sin^2 \frac{\omega t}{2} + \lambda) \\ C_{b-B} &= C(\cos^2 \frac{\omega t}{2} + \lambda) \\ C_{a-B} &= C(\cos^2 \frac{\omega t}{2} + \lambda) \end{aligned} \tag{56}$$

where λC is the minimum capacitance and C the maximum capacitance change between any stator and any rotor group.

The analysis now proceeds as before, the simpler case of a pure resistance R in the external circuit being treated. The voltage across the slip rings is found to be

$$e = \frac{V}{\sqrt{(1+2\lambda)^2 + \left(\frac{2}{CR\omega}\right)^2}} \cos(\omega t - \phi) \tag{57}$$

and

$$p = \frac{V^2}{R\left[(1+2\lambda)^2 + \left(\frac{2}{CR\omega}\right)^2\right]} \cos(\omega t - \phi) \tag{58}$$

where

$$\phi = \tan^{-1} \frac{2}{CR\omega(1+2\lambda)} \tag{59}$$

$$P_a = \frac{V^2}{2R\left[(1+2\lambda)^2 + \left(\frac{2}{CR\omega}\right)^2\right]} \tag{60}$$

The condition for maximum average power, $\partial p/\partial R = 0$, is realized when

$$R = \frac{2}{C\omega(1+2\lambda)} \tag{61}$$

The ratio of the maximum average power of a given machine to its maximum average power, if no parasitic capacitances were present, is

$$\frac{P_m(C+C_o)}{P_m} = \frac{1}{1+2\lambda} \tag{62}$$

It is seen that the effect of the parasitic capacitances C_o is to reduce the alternating current, voltage, and power, of this type of synchronous electrostatic machine.

8. Polyphase Synchronous Electro-Static Machines, Type 2

Polyphase machines of this type have been devised. A schematic diagram for one of the several connections for a three-phase machine is shown in Fig. 9. The above analyses of single-phase machines apply to each phase of the polyphase machines. Polyphase operation results in a uniform torque characteristic. This type of machine, whether single or polyphase, is further characterized by the absence of current harmonics.

C. DIRECT-CURRENT ELECTROSTATIC GENERATOR - TYPE III

This machine was devised during the course of this investigation.* A multipolar generator of this type is illustrated in Fig. 10 and schematically in Fig. 11. The interleaving rotor and stator members are of metal and so arranged that with rotation of the rotor the capaci-

---

* By R. J. Van de Graaff, August 15, 1933.

tance between them varies cyclically between a minimum value C_o and a maximum value C_m. The rotor is insulated from ground and maintained at a voltage V relative to ground by an auxiliary means to be described. The stator is connected to the junction of two electronic valves which are connected in series across the line. To generate negative electric power, the rotor-inducing voltage V must be positive and the valves must be connected as shown in Fig. 11. To generate positive electric power, V must be negative and the valves reversed.

1. Theory of Operation

Referring to Fig. 11, C is the capacitance between rotor and stator in any position, C_o and C_m are the minimum and maximum values of C, C_ℓ is the lumped capacitance of the external power system, C_s is the capacitance of the stator relative to ground, C_{v1} and C_{v2} are the capacitances of valves 1 and 2 to ground, V and E are the inducing voltage on the rotor and the output line voltage, respectively, both expressed relative to ground and both assumed at first to be constant.

The cycle for the generation of negative electric power is as follows: When C becomes equal to C_m, Valve 2 ceases to be conducting. At this point the stator is at ground potential, full line voltage E exists across Valve 1, and full inducing voltage V exists across C_m. The electric charge stored between rotor and stator is therefore

$$Q_m = C_m V \tag{63}$$

As the rotor turns, the capacitance C diminishes. Since neither valve is now conducting, the voltage across C increases, the stator becoming more and more negative relative to ground. The stator attains line potential E when

$$C_1 = \frac{C_m V-(C_s+C_{v2})E}{E+V} \tag{64}$$

At this point (assuming, for simplicity, zero drop across the valves when conducting) Valve 1 becomes conducting. Further movement of the rotor till $C = C_o$ causes charge to leave the stator and flow onto the line. Valve 2 is now withstanding full line voltage E. The charge left in the generator system when $C = C_o$ is

$$Q_o = C_o(E+V)+(C_s+C_{v2})E \tag{65}$$

As the capacitance now increases, due to the isolation of the charge Q_o, the potential of the stator approaches ground potential. The stator reaches ground potential and Valve 2 becomes conducting when

$$C_2 = \frac{Q_o}{V} = \frac{C_o(E+V)}{V} + \frac{(C_s+C_{v2})E}{V} . \tag{66}$$

Charge continues to flow into the stator from ground until $C = C_m$ when the cycle repeats.

The net amount of electricity transferred during a cycle is

$$Q = Q_m-Q_o = C_m V-\left[C_o(E+V)+(C_s+C_{v2})E\right] \text{ coulombs} \tag{67}$$

The number of cycles per second is given by

$$f = \frac{n\ p}{60} \tag{68}$$

The power output of this machine is therefore

$$P_a = \frac{np\ VE}{60}\left[C_m- \frac{C_o(E+V)+(C_s+C_{v2})E}{V}\right] \tag{69}$$

In terms of the physical dimensions of the machine, the power output is

$$P_a = 4.63 \times 10^{-15} \frac{knsp(r_1^2-r_2^2)VE}{d} \text{ watts} \tag{70}$$

where

$$k = 1 - \frac{C_o(E+V)+(C_s+C_{v2})E}{C_mV} \tag{71}$$

n = revolutions per minute
s = number of rotor plates
d = separation between rotor and stator in centimeters
r_1 and r_2 = radii of rotor in centimeters

A practical idea of the value of k is obtained as follows: Assuming $C = 0.1\, C_m$, $C_s+C_{v2} = 0.25\, C_o$, $E = V$, then $k = 0.775$.

2. Effect of Variation of Inducing Potential V_1

It is evident that the rotor is capacitively coupled to ground, and that the value of this capacitance, due to motion of the rotor, varies* between C_r+C_m and C_r+C_o. If the rotor is initially charged to voltage V when its capacitance to ground is C_r+C_m, then the potential of the rotor, when $C = C_o$, is

$$V' = \frac{C_r+C_m}{C_r+C_o} V \tag{72}$$

Since, in general, large fluctuations in the rotor potential are undesirable, it is seen that C_r should be large relative to C_m. If C_r is 10 C_m, then in any practical machine the voltage V would undergo a maximum increase of about 10 per cent. The maximum voltage between stator and rotor occurs when $C = C_o$ and is equal to

$$E_{max} = E + \frac{C_r+C_m}{C_r+C_o} V \tag{72}$$

The effect of this increase in inducing voltage is also to reduce the power output, since the charge left in the system, when $C = C_o$, is

---

* Assuming $C_\ell \to \infty$ and $C_s \to C_v \to 0$.

$$Q_o = C_o(E+V')+(C_s+C_{v2})E \tag{73}$$

It must be noted that the rotor performs simply an inducing function and that, once charged, it requires electrical energy only to replace the leakage across its insulators.

3. The Reduction of the Undesirable Effect of Varying Inducing Voltage

A simple means may be used to reduce the undesirable effect of variation in the inducing potential V_o. This is done by displacing one-half of the stator plates 90 degrees relative to the others. Separate electronic valves must now be used for each set of stators. By this means the total capacitance between rotor and stator remains constant for all positions of the rotor.

The inducing voltage V depends, once the system has been charged, on the total capacitance rotor to ground. This does not become constant by the above artifice since the connections of the stator change during the cycle. Fig. 12 illustrates the circuit connections for the simple machine during the cycle. Fig. 12-a describes the interval from $C = C_m$ to $C = C_1$ during which the stator changes from ground to line potential. Fig. 12-b describes the connection from $C = C_1$ to $C = C_o$. This is the discharging interval. Fig. 12-a again describes the interval from $C = C_o$ to $C = C_2$, during which the stator changes from line to ground potential. Fig. 12-c describes the charging interval from $C = C_2$ to $C = C_m$.

Fig. 13 shows the variation of total rotor capacitance to ground during a cycle for the constant rotor-stator capacitance machine with a doubly-displaced stator. The curve is drawn using the practical assumptions that C_{v1}, C_{v2}, and C_s are closely zero capacitances, C_ℓ is a relatively infinite capacitance, and $E = V$.

It is evident that in a machine in which the stator and rotor plates have been staggered once in the manner described, so as to secure constant rotor-to-stator capacitance, the rotor-to-ground capacitance variation is one-half what it was before. By still further staggering the stators, further reduction of the inducing system voltage variation can be effected.

4. Output Current and Voltage Characteristic

The generator with the two 90-degree-displaced sets of stators evidently has two current-conduction intervals during each cycle. This results in a more uniform output-current characteristic. By the use of four sets of stators, displaced successively 45 degrees along the cycle and with four sets of electronic valves, the current input to the line would be nearly constant for the case where $V = E$. Actually, by proper design, such a uniform current characteristic can be very closely realized. The high frequency of the current pulses, brought about by the high speed of rotation and the large number of poles which characterize these electrostatic generators, coupled with the high capacitance of the output circuit, is effective in preventing large voltage ripples.

5. Power Control

The power output of this generator for any given line voltage can be regulated by controlling the rotor inducing voltage V_o. This rotor voltage may be maintained by a low-power electrostatic generator of the collector type operating in the same vacuum. Other means have also been devised. The potential V may be controlled, for example, by changing the resistance of a high-resistance leak.

D. DIRECT-CURRENT ELECTROSTATIC GENERATOR - TYPE IV

This generator was devised during this investigation. It is illustrated in Fig. 14 as a two-pole generator, for simplicity. Since the power of a machine of given dimensions is proportional to the number of poles, it is desirable for high power concentration to employ many poles. The generator consists of two sets of stator plates, a and b at line potential and at ground potential, respectively, and two sets of rotor plates, A and B insulated from ground and each other for full line voltage.

1. Cycle of Operation

The cycle of operation is as follows: In Position 1-1, rotor sectors A and B are at the same potential because of symmetry, this potential being one-half of the line potential. At this position an electrical connection is made between A and B which is maintained until Position 2-2. During this interval charges are induced on the rotor sectors which are isolated when the connection A to B is broken at Position 2-2. No net motor action is developed over this interval, since equal amounts of motor and generator action are developed. As the rotor continues to turn, an optimum position is reached where the potential of A becomes the same as that of b, and the potential of B the same as that of a. At this optimum position connections between A and b and between B and a are established. These connections are maintained until the rotor is in Position 3-3 where A is completely within the Faraday cage formed by b, and B completely within the Faraday cage a. At this position A is neutral and at the same potential as b; likewise B is neutral and at the same potential as a, and the discharge circuits are opened. Sectors A and B now move to the position of symmetry 1-1 where the cycle starts anew.

2. Power Capacity of Direct-Current Electrostatic Generator - Type IV

The maximum charge isolated on the rotor sectors during the charging interval from Position 1-1 to 2-2 is $C_m E/2$ or

$$Q = \frac{0.0884 \times 10^{-12}\ \pi(r_1^2 - r_2^2)2s}{2d}\ \frac{E}{2} \tag{74}$$

where C_m is the maximum capacitance rotor to stator in farads, E is the line voltage, r_1 and r_2 are the outer and inner radii of the metal rotor in centimeters, and d is the separation between rotor and stator in centimeters. The capacitance C_m is here taken as one-half that which would be obtained if the physical arrangement of the rotor and stator were as shown in Fig. 14. In any actual machine the rotor sectors A and rotor sectors B would be in two separate sections along the shaft. This permits one-piece rotor construction with resultant high mechanical strength, but reduces the total capacitance for a given number of rotor disks by a factor of two. This construction is illustrated in Fig. 15 and applies to many of the direct-current machines discussed herein.

The number of cycles per second is given by

$$f = \frac{np}{120} \tag{75}$$

The maximum average power developed by the generator is therefore

$$P_m = 0.58 \times 10^{-15}\ \frac{nps}{d}\ (r_1^2 - r_2^2)E^2 \text{ watts} \tag{76}$$

It is noted that the ratio of the maximum average power of a given-sized generator of Type IV to that of Type III, both operating on the same line voltage E, is

$$\frac{P_{IV}}{P_{III}} = \frac{E}{8KV} \qquad \text{where } K < 1. \qquad (77)$$

The maximum voltage between rotor and stator in the Type IV generator, however, is E, whereas this maximum voltage in Type III is E+V. If the insulation limitation on these generators is a voltage limitation, it is clear that the Type IV generator can operate safely at a line voltage which is E+V/E times that of the safe operating voltage of Generator III.

The ratio of the maximum average power of a given-sized generator of Type IV to that of Type III, when both are subjected to the same maximum electric stress between rotor and stator, is

$$\frac{P_{IV}}{P_{III}} = \frac{1}{2K} \qquad \text{where } K < 1. \qquad (78)$$

3. Method of Making and Breaking Connections

During the first part of the cycle A and B are electrically connected. This connection is always made at the same point in the cycle and at a time of zero voltage difference and zero current flow. Hence such a connection could easily be made mechanically by a commutating mechanism such as is described on p. 72. This connection is broken in Position 2-2. The mechanical design is such that at this position there is again a short period of small or zero capacitance change. The connection is broken at the beginning of this interval, the current and voltage being zero when the contacts separate, and remaining so for a short period thereafter. The schematic diagram for this commutator is shown in Fig. 14. It is evident that this commutation is under ideal conditions. By inserting an electronic switch in series with this inter-rotor connection, the necessity for close timing of the commutator contacts is eliminated, the switch automatically performing this function. By controlling the grid of this switch the amount of charge isolated on the rotors can be controlled. This offers a means of controlling the power developed by this generator and will be discussed below.

The discharge of the rotor sectors into the line sectors begins (for highest efficiency) when the rotors attain exactly their respective line potentials. Mechanical commutation, illustrated in Fig. 14, is used to accomplish this. While under any given conditions the optimum position for this commutation is always at the same point in the cycle, under varying load conditions this optimum position varies, coming later in the cycle for lighter loads. Accordingly the mechanical commutator is arranged so that the proper circuit connections are established at the earliest possible point in the cycle at which the optimum condition can occur, and an electronic valve is inserted in series with these connections so that actual transfer of charge cannot take place until the optimum conditions obtain. This results in high efficiency of charge transfer under all conditions, and relieves the mechanical commutation from all precise timing requirements.

The type of electronic valve proposed for use with these machines is described in Chapter VIII. This method of simultaneous mechanical commutation and electronic commutation is applicable to and intended for all of the machines described herein.

4. Power Control

The power developed by the line-excited generator, Type IV, may be controlled in several ways. This discussion will be based on the existence of a constant line voltage E.

(a) By opening the connection between rotors A and B at some position between 1-1 and 2-2, the amount of charge isolated on them is less than the maximum amount. This may be accomplished automatically by a grid-controlled electronic switch, as suggested above. The grids of these switches may, for example, be actuated by changes in the line voltage in such a way as to keep the line voltage constant. The use of the electronic valves in the output circuit, as suggested above and as shown in Fig. 14, permits the flow of the charge into the line under optimum conditions for all loads. In this way the power output of the generator may be either manually or automatically regulated for efficient operation over the entire range.

(b) Again, it is possible to regulate the power output of the machine by dividing it into several independent sections and providing manual or automatic means for large-stepped variations of power by tripping out the desired number of sections, the remainder operating at maximum power output. The sections may be cut out by simply failing to connect rotor sectors A and B during the inducing period. Simple electrostatic and electromagnetic schemes for accomplishing this have been devised. This method has the advantage that the commutation positions in the active cycles are constant. By providing the last section to be tripped out similarly with further subdivisions, it is evident that the power gradations can be made very small. This last section might also be arranged to provide variable power by the electronic method suggested under (a).

(c) The power output of this machine can also be regulated by controlling the speed of the prime mover. This method has the advantage that the optimum commutating positions are not displaced with load. It has its limitations in the high energy of the moving system and the consequent time delay involved in changing load. The freedom of the electrostatic system from the constant-speed requirement, however, makes this method valuable for certain applications.

The general ideas involved in these power-control methods are applicable to each of the various types of machines described herein.

E. DIRECT-CURRENT ELECTROSTATIC GENERATOR - TYPE V

This generator was devised during this investigation. It is of the separately-excited classification and is illustrated diagrammatically in Fig. 16. It consists essentially of two sets of metallic stator sectors, Sectors a being maintained at an inducing voltage +V above the positive line voltage E, and Sectors b being maintained V volts negative relative to the negative line, which may be taken as at ground potential. The two sets of metallic rotor sectors, A and B, are insulated from each other and ground for full line voltage. In any practical machine these rotor sets would be displaced from each other along the shaft to secure maximum mechanical strength of the rotating parts. Such a practical construction is illustrated in Fig. 17.

1. Cycle of Operation

Referring to Fig. 16, the cycle of operation is as follows: When the metallic rotors A and B are within the Faraday cages formed by the stator sectors a and b, respectively, Sector A is electrically connected to the positive line, and B to the negative line or ground. For maximum power these electrical connections between rotors and lines are opened in Position 1-1 where the capacitances C_{A-a} and C_{B-b} are maximum. This results in the isolation of negative charge of amount $C_{A-a}V$ on Rotor A, and of $C_{B-b}V$ on Rotor B. With further movement of the rotor these capacitances diminish, the potential of A approaching ground potential, and that of B approaching the positive-line potential. It is evident that, as Rotor Sector A with its isolated negative charge moves into the negatively-charged Faraday cage formed by b, the potential of A tends to become even more negative than b. Likewise, B tends to become even more positive than a. There is, therefore, a certain intermediate point in the movement of the rotor from Position 1-1 where A attains ground potential and B attains the positive-line potential. At this optimum position A is electrically connected to ground, and B to the line. Electronic valves in series with mechanical commutators, as illustrated in Fig. 16, may be used to assure these connections at the optimum point. Movement of A into b, and of B into a, now causes the isolated charges to flow into the system and further charges to be induced on the rotors. The electrical connections between rotors and lines are maintained (for maximum power) until A is fully within b, and B within a. This is again Position 1-1, and the cycle repeats.

2. Power Capacity

The maximum charge isolated on the rotor sectors of a practical generator during a cycle is

$$Q = C_m V = \frac{0.278 \times 10^{-12} (r_1^2 - r_2^2) sV}{d} \qquad (79)$$

The number of cycles per second is given by

$$f = \frac{np}{60} \qquad (80)$$

The maximum average power developed is

$$P_m = \frac{4.63 \times 10^{-15} \, nps(r_1^2 - r_2^2)VE}{d} \tag{81}$$

The maximum voltage between rotor and stator is E+V.

3. The Inducing Voltages, V

The inducing stators a and b are connected capacitively to their respective lines and charged to the potential +V and -V relative to them. No power is required to maintain these charges except to replace the leakage loss to the lines. Unless the capacitances of the stator sectors to their respective lines is very large, the voltages V will vary during the cycle, due to the movement of the rotor. Any large variation of this kind is undesirable since, for a given amount of developed power,it increases the voltage-insulation requirement in a manner similar to that discussed in the case of the Type III generator. This variation may be very considerably reduced by dividing the machine into two machines, the stators being in the same relative position for both of them, but the rotors displaced by 90 degrees. Division into four machines, and the relative displacement of the rotors by 45 degrees, offers still further advantages. It is evident that another important effect of such a multiple displacement of rotors is that the output current can be made quite uniform.

The inducing voltages V may be maintained by means of low-power electrostatic generators of the types disclosed herein.

4. Power Control

The current output of this generator can be regulated by controlling the inducing potentials, V. This could be done by means of automatically- or manually-controlled leaks which, acting against the inducing generators, would establish the inducing potentials relative to the lines at any desired value. The current can also be controlled by the methods suggested in paragraphs a, b, and c of Item 4, Generator Type IV.

F. DIRECT-CURRENT ELECTROSTATIC GENERATOR - TYPE VI

This generator* is of the line-excited type and is illustrated diagrammatically in Fig. 18. It consists essentially of two sets of metallic stators, sectors a and b, which are connected to the positive and negative lines, respectively, and two sets of metallic rotors A and B, which are electrically insulated from the shaft and each other. It is intended, though not necessary, that each "set" be multipolar. In any practical machine it is expected that all the rotor sectors performing the function of Sectors A will be constructed as a balanced metallic unit - similarly for those performing the function of B - and that these two rotor units will be mounted separately along the shaft and insulated from the shaft and each other for full line voltage. This construction, illustrated in Fig. 25, results in maximum mechanical and electrical strength. The general idea of securing balanced unit rotor construction is applicable to all the machines herein described, though the machines are not limited to this construction.

1. Cycle of Operation

In Position 1-1 rotor sectors A and B are in a symmetrical position relative to the stator sectors a and b and are hence at the

---

[*] Developed by R. J. Van de Graaff during and prior to September, 1929.

same intermediate potential, namely, one-half the line voltage E. At this position the rotor sectors are electrically connected together by some means such as the commutator indicated in Fig. 18. In the interval from Position 1-1 to 2-2 motor action is developed between A and a, and between B and b. This motor force is at all times in this interval proportional to $\frac{E^2}{2}\frac{dC}{d\theta}$ where C is the capacitance between A and a, or B and b. When the rotor plates are fully interleaved with the stator and at a time of no current flow, Position 3-3, the electrical connection between A and B is broken. This isolates the charges which have been induced on sectors A and B. Further movement now carries these isolated charges toward those stator sectors charged with electricity of the same kind. At the optimum position, when the rotor sectors attain the potential of the line sectors, the isolated rotor charges are allowed to start flowing to the lines, the charge on A flowing to b, and the charge on B flowing to a. This transfer of charge may be accomplished under optimum conditions by careful timing of mechanical commutation, or by the series combination of mechanical and electronic valve commutation which has already been described. When the transfer of charge has been completed, that is, when the rotor sectors A and B are completely within the Faraday cages b and a, respectively, the discharge circuits are opened. Further movement of the now neutral rotor sectors carries them out of the Faraday cages and to the position of symmetry 1-1; the cycle then repeats.

2. Power Capacity

The maximum charge isolated on the rotor sectors of a practical generator of this type during one cycle is

$$Q_m = \frac{C_m E}{2} = \frac{0.0694 \times 10^{-12}\ (r_1^2 - r_2^2) s E}{d} \qquad (82)$$

The number of cycles per second is

$$f = \frac{np}{120} \tag{83}$$

The maximum average power developed is

$$P_m = \frac{0.289 \times 10^{-15} \times nps(r_1^2-r_2^2)E^2}{d} \text{ watts} \tag{84}$$

The maximum voltage between rotor and stator is the line voltage E.

It is seen that the maximum average power developed by a Type VI generator of given physical size is one-half that of a Type IV generator. The interval of motor action during the generator cycle which characterizes the Type VI generator is not present in the Type IV generator. Both types, under given conditions, are subject to the same maximum electric stress.

3. Power Control

The methods of power or current control described for the Type IV generator apply to the Type VI generator. The general schemes for effecting the electrical connections apply to both types.

G. DIRECT-CURRENT ELECTROSTATIC MOTOR - TYPE VII

This direct-current electrostatic motor was developed during this investigation. A simplified diagram of this machine is given in Fig. 19. This machine differs from all the other machines described herein, in that the general principle of transferring charge from one capacitive system to another only when they are at closely the same potential is not observed. This results in a definite amount of energy loss in the operation of this machine as a generator. A quantitative discussion of this characteristic is made below.

1. Cycle of Operation

Since, as will become evident, Rotor Sector B goes independently through a similar cycle as Rotor Sector A, the cycle of operation will be described for Sector A alone.

The cycle may be considered to start when Rotor Sector A is about to leave the Faraday cage formed by Stator Sector a. Contact between A and a still exists from the previous cycle. Sector A then moves to some position such as that shown in Fig. 19. At this position contact between A and a is broken, a charge Q equal to C_1E being isolated on Rotor Sector A where C_1 is the capacitance at that instant between A and b, and E is the line voltage. Further movement causes C_{A-b} to increase for either or both of the following reasons:

(a) Because of increase in the effective overlapping areas of sectors A and b.

(b) Because of a decrease in the separation between A and b produced, for example, by increasing thickness of stator plates with angle, or of rotor plates with angle, or both. These methods are described in further detail in Item B of Chapter III. The design may be such that the maximum capacitance C_{A-b} is attained just when A is about to leave the Faraday cage formed by b. At this position the voltage between A and b has decreased to the value EC_1/C_m. Rotor Sector A is discharged into the stator sector b at this point by contact or by other means. The cycle is now complete.

2. Power Capacity

The charge isolated on the rotor of a practical form of motor of this type during one cycle is

$$Q = \frac{.278 \times 10^{-12}\ KsE(r_1^2-r_2^2)}{d} \text{ coulombs} \tag{85}$$

where K is the ratio of the effective area of the rotor overlapping the inducing stator sector at the end of the charging period, to the total rotor area.

The voltage at the time of discharge of the rotor into the stator sector is

$$V = E\,\frac{Kd'}{d} \tag{86}$$

where d' is equivalent separation between rotor and stator in the position of maximum capacitance. The frequency of the motor is given by

$$f = \frac{np}{60} \tag{87}$$

The average power developed by the motor is

$$P_a = \frac{4.63 \times 11^{-15}\ nsp(r_1^2-r_2^2)E}{d} \left[K-K^2\,\frac{d'}{d}\right] \text{watts} \tag{88}$$

The percent of energy loss relative to the motor output is given by

$$\text{Percent loss} = \frac{100\ K^2\,\frac{d'}{d}}{K-K^2\,\frac{d'}{d}} \tag{89}$$

If K = 0.4 and d'/d = 0.1, then the percentage of energy loss is 4.2 per cent.

3. Power Control

The amount of power developed by this motor can be regulated by controlling the position at which the connections between the stator sectors and the departing rotor sectors are broken. This may be done by means of a mechanical commutator or by means of a grid-controlled electronic valve. Definite mechanisms for controlling these switching devices automatically so as to maintain constant speed, or other output characteristics, have been devised.

H. DIRECT-CURRENT ELECTROSTATIC MOTOR - TYPE VIII

This motor differs from the Type VII motor in the introduction of an artifice to eliminate the energy loss involved in the power cycle of that machine.* A diagrammatic sketch of this improved electrostatic motor is given in Fig. 20.

1. Cycle of Operation

It is seen from Fig. 20 that Stator Sector a is maintained positive relative to Line a, and Sector b neg relative to Line b, by an inducing potential of V volts. This inducing potential V is such that the charged rotor sectors A and B can attain line potential and therefore, at the end of each motor interval, can be connected to the lines at the time of no voltage difference. This permits the transfer of charges between rotor and lines under optimum conditions. For example, when Sector A, carrying its isolated positive charge, approaches the negative inducing Sector b, the capacitance C_{A-b} increases and the voltage between them diminishes. The design is such that this voltage difference (at the position of maximum capacitance C_{A-b}, and if the charge were to remain isolated on A) would become equal to or less than the inducing voltage V. Hence there must exist a point where the potential of the rotor sector A and Line b are the same. At this optimum point connection between A and Line b is established. This connection is maintained until A has not only released its positive charge to the line, but has also emerged from the sectors b sufficiently to have

---

* Suggested by R. J. Van de Graaff.

acquired a negative charge of the desired amount by induction from Stator Sector a. Connection between A and Line b is then broken. The cycle now repeats. Evidently this arrangement has eliminated the power loss associated with sudden condenser discharges. A similar cycle, with charges of the opposite sign, is independently undergone at the same time by B and a. The current and torque characteristic can be made quite uniform by staggering the rotors in phase position relative to one another, keeping the stators in the same position. Each separate set of rotors must then have a separate commutating system.

2. Power Capacity

The charge isolated on the rotor of this machine during one cycle is given by

$$Q = \frac{.278 \times 10^{-12}\ rsV(r_1^2 - r_2^2)}{d} \tag{90}$$

where r is again the ratio of the capacitance at the end of the charging interval to the maximum capacitance rotor to stator.

The average power developed by this motor is

$$P_a = \frac{4.63 \times 10^{-15}\ nrsp(r_1^2 - r_2^2)E^2}{d} \text{ watts} \tag{91}$$

The maximum voltage between rotor and stator is E+V. For high efficiency this voltage must be at least equal to E(1+r). If r = 1, it is seen that the power concentration and the required insulation strength are precisely the same as in the Type V generator described below.

I. DIRECT-CURRENT ELECTROSTATIC MOTOR - TYPE IX

This direct-current electrostatic motor was developed during this investigation. It consists essentially of two sets of metallic stator members which are connected to the two lines of the power supply, and two sets of metallic rotor members which interleave with the stator and are insulated from the stators and from each other for full line voltage. A diagrammatic sketch is given in Fig. 21.

1. Cycle of Operation

When the rotor is in the position of symmetry 1-1, Stator Sector A is connected to the negative line and Stator B to the positive line. This may, for example, be accomplished by a commutator, as illustrated. Full voltage thus exists between A and a, and between B and b, and motor action is developed as the rotor moves clockwise. In Position 2-2, when the capacitances C_{A-a} and C_{B-b} have reached one-half their ultimate maximum capacitances, the lines are disconnected from the rotor sectors and the charges on them isolated. As the rotor moves from Position 2-2 to 3-3, these capacitances increase from C/2 to C and hence the voltage between A and a, and between B and b, diminishes from E to E/2. At Position 3-3 the voltage between rotor sectors A and B is therefore zero and there is no current when they are electrically connected in this position. The interval from Position 1-1 to 3-3 is characterized by motor action. As the rotor now continues to advance toward Position 4-4, the capacitances C_{A-a} and C_{B-b} diminish, the voltages across them remaining at E/2. At Position 4-4, where these capacitances are two times their minimum values, rotor sectors A and B are disconnected. This isolates the charges on the rotor sectors so that at the position of minimum capacitance 5-5, corresponding to the starting position of the cycle, the rotor sectors will have attained the voltages of the lines to which they are about to be connected. The interval from 3-3 to 5-5 is characterized by generator action. This power cycle is illustrated in Fig. 22.

2. Power Capacity

The maximum charge which is transferred during each cycle is

$$Q = \left(\frac{C_m E}{2} - C_o E\right) \tag{92}$$

and the voltage through which this charge falls is one-half the line voltage, or E/2.

The frequency of this process is given by

$$f = \frac{np}{60} \tag{93}$$

The maximum average power developed by this motor is, therefore,

$$P_a = \frac{np}{60}\left(\frac{C_m E}{2} - C_o E\right)\frac{E}{2} \text{ watts} \tag{94}$$

In terms of the physical constants of a practical machine of this type this is

$$P_a = \frac{.578 \times 10^{-15}\ Knps(r_1^2 - r_2^2)E^2}{d} \text{ watts} \tag{95}$$

where

$$K = \frac{C_m - 2C_o}{C_m}$$

The maximum voltage between the rotor and stator is the line voltage E.

For the same maximum electric stress and physical size, the ratio of the power developed by the Type IX to the Type VIII motor is given by

$$\frac{P_{IX}}{P_{VIII}} = \frac{K}{2} \qquad \text{where } K < 1 \tag{96}$$

3. Power Control

The power developed by this motor may be controlled by regulating the time in the power cycle at which the rotors are disconnected from the lines. This can be accomplished by mechanical commutators or by means of grid-controlled switches in the rotor-to-line circuits. These grid-controlled switches could be provided with automatic features to maintain constant speed at all loads, for example.

Again, the motor may be divided into sections, and one of these still further into sections, each of these sections serving as a separate motor. Adjustment to load could be accomplished by cutting in or out the requisite number of sections, the active sections always operating under the condition for maximum power. This is a general method, applicable to all the machines discussed herein, and has been described with reference to generators on p. 42. The sections could be cut out by various simple means; for example, by failing to make the rotor-to-line connection or by failing to interconnect the rotors.

J. DIRECT-CURRENT ELECTROSTATIC MOTOR- TYPE X

This electrostatic motor was developed during this investigation. It departs from the Type IX motor in that no interval of generator action exists during the power cycle. This results in higher power concentration. This motor is diagrammatically illustrated in Fig. 24.

1. Power Cycle

When the rotor is in Position 1-1, Rotor Sector A is electrically connected to the negative-power line, and Rotor Sector B to the positive line. As will be shown, sectors A and B in this position are as neutral bodies inside a Faraday cage, and hence there is no current at the moment this connection is made. With clockwise rotation a motor force proportional to $E^2 \, dc/d\theta$ is developed, where C is the capacitance between A and a, or between B and b. For maximum power (at high efficiency) the rotor sectors are disconnected from the line when Position 2-2, corresponding to one-half the maximum of C_{A-a} or C_{B-b}, is reached. This disconnection can be effected by actual separation of contacts or by means of a grid-controlled vacuum switch. Motor action of diminishing magnitude now continues until Position 3-3 is reached, corresponding to the maximum values of C_{A-a} and C_{B-b}. At this position rotor sectors A and B attain the same potential, E/2, and are electrically connected. Rotation continues to Position 4-4, where the capacitances are again at one-half their maximum values, and the connection between A and B is broken. The net charge thus isolated on each of the rotors is evidently zero. Further rotation brings these rotor sectors into Position 5-5, which is identical with starting position 1-1. Here, since they are in a neutral condition, they acquire the potential of the Faraday cages in which they are located. This completes the cycle.

2. Power Capacity

The maximum charge isolated on the rotors of a practical motor of this type is

$$Q = \frac{0.139 \times 10^{-12} \, (r_1^2 - r_2^2) sE}{d} \quad \text{coulombs} \tag{97}$$

The number of power cycles per second is given by

$$f = \frac{np}{120} \tag{98}$$

The maximum average power developed by the motor is

$$P_a = \frac{0.578 \times 10^{-15}\ nps(r_1^2-r_2^2)E^2}{d}\ \text{watts} \tag{99}$$

The maximum voltage between rotor and stator is the line voltage E.

The ratio of the maximum power, per unit size and for the same maximum electric stress, developed by the Type X motor, to that developed by the Type VIII motor is

$$\frac{P_X}{P_{VIII}} = \frac{1}{2} \tag{100}$$

3. Power Control

The power developed by this machine may again be controlled by any of the aforementioned methods.

(a) By controlling the position at which the rotor sectors are disconnected from the line. It is then desirable to introduce a one-way electronic valve in series with the circuit which connects the two rotors so that the charge will commence to flow between them under the optimum condition, i.e., when zero potential difference exists, for all load conditions.

(b) By sectionalizing the motor and cutting in and out sections, manually or automatically, as required.

K. GENERAL REMARKS

Fig. 23 sums up briefly the essential characteristics of the vacuum electrostatic power machines discussed herein. Several other types of machines have been devised which are not here included.

In general, in vacuum electrostatic machines the roles played by the rotor sectors and the stator sectors may be changed without change in operating principle. The particular arrangements used in describing these machines were chosen for simplicity, but practical machines are not necessarily limited to these.

Vacuum electrostatic power machines exhibit two interesting and important departures (in addition to those already cited) in operating characteristics from those of electromagnetic power machines. They possess no inherent damping action to suppress machine oscillation, as, for example, the eddy currents in the electromagnetic case. They possess no equivalent of the counter e.m.f. of electromagnetic motors to limit the speed. Both of these characteristics introduce problems special to electrostatic machines.

FIGURE 1

SYNCHRONOUS VACUUM ELECTROSTATIC POWER MACHINE - TYPE 1

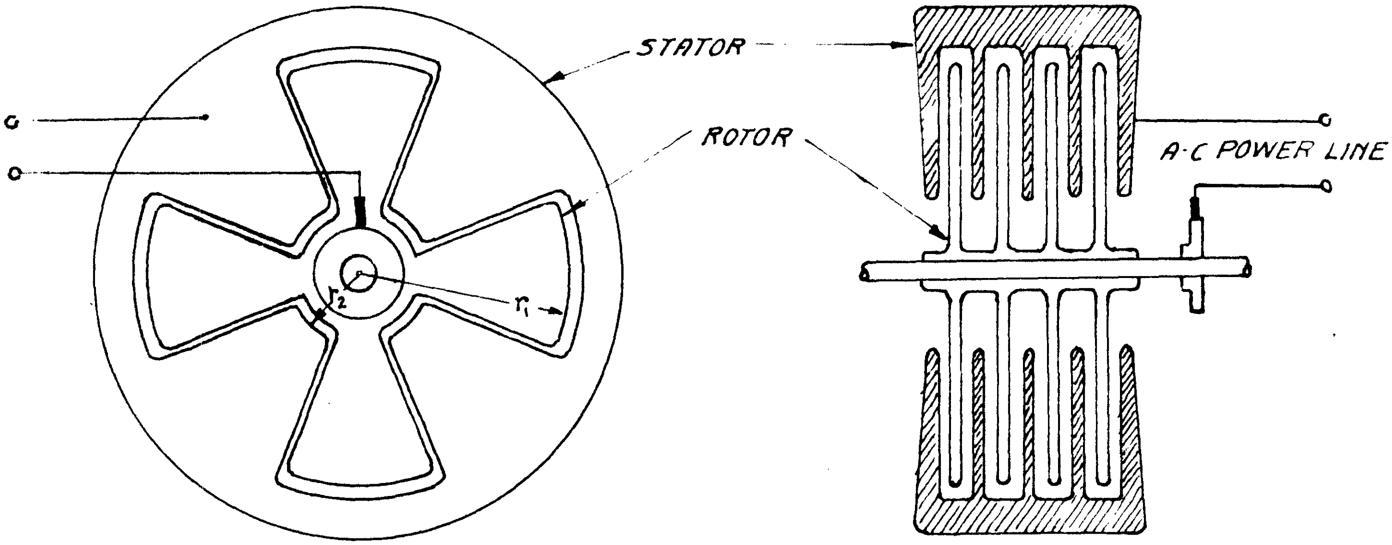


FIGURE 2

CHARACTERISTIC CURVES FOR SYNCHRONOUS ELECTROSTATIC MACHINE - TYPE 1 - SHOWING VOLTAGE, CAPACITANCE, & POWER VARIATION.

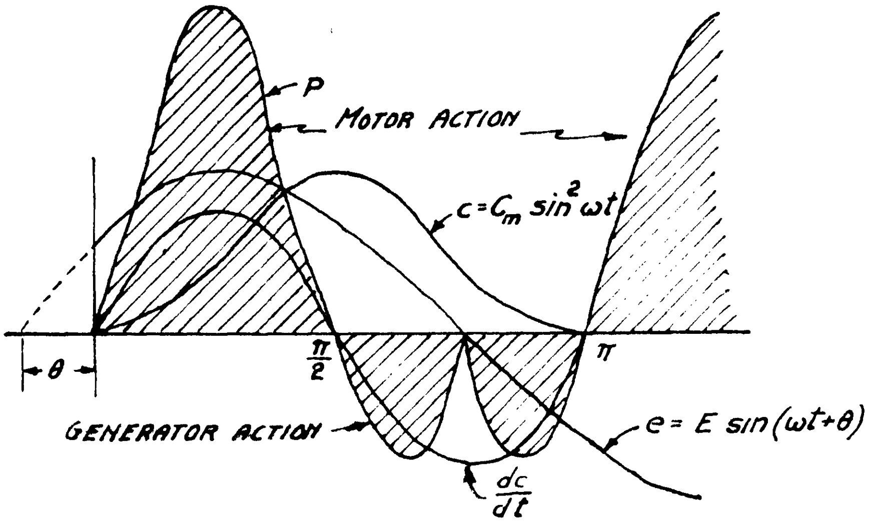


FIGURE 3

FOURIER ANALYSIS OF A RECTANGULAR WAVE.

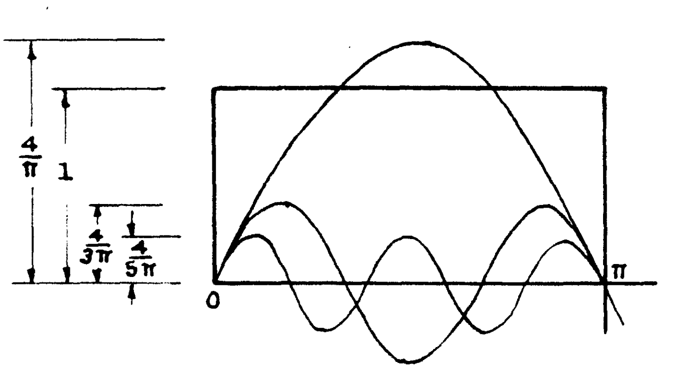


FIGURE 4

EFFECT OF MINIMUM CAPACITANCE ON CURRENT AND POWER FACTOR OF TYPE 1 MACHINE.

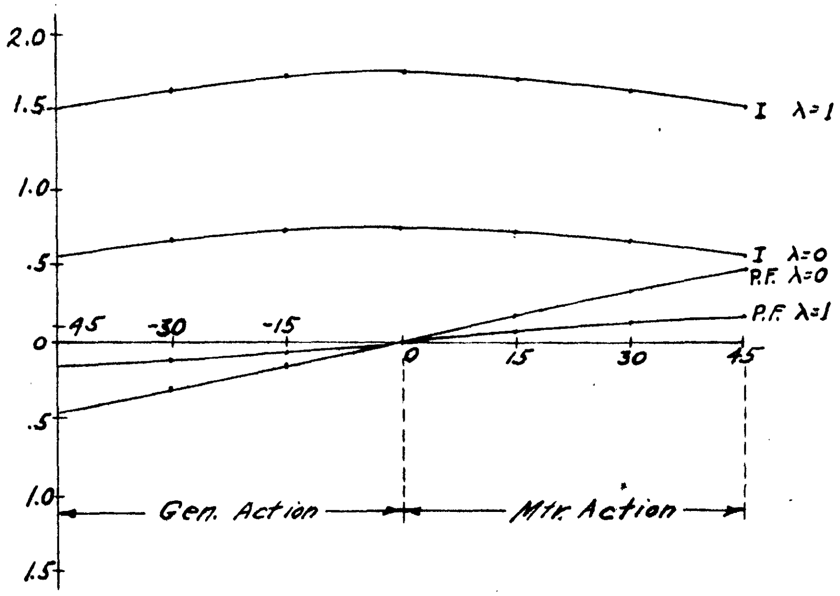
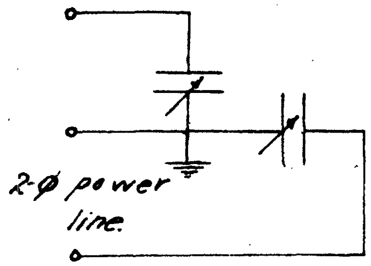
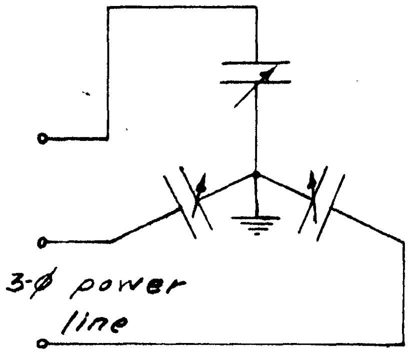


FIGURE 5

SCHEMATIC OF 2-φ MACHINE -- TYPE 1



SCHEMATIC OF 3-φ MACHINE -- TYPE 1.



3-φ CONSTRUCTION

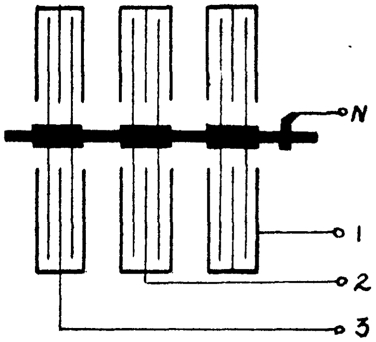


FIGURE 6

TRANSFORMER CONNECTIONS FOR THE ELIMINATION OF THIRD HARMONIC, DUE TO TYPE 1 MACHINE.

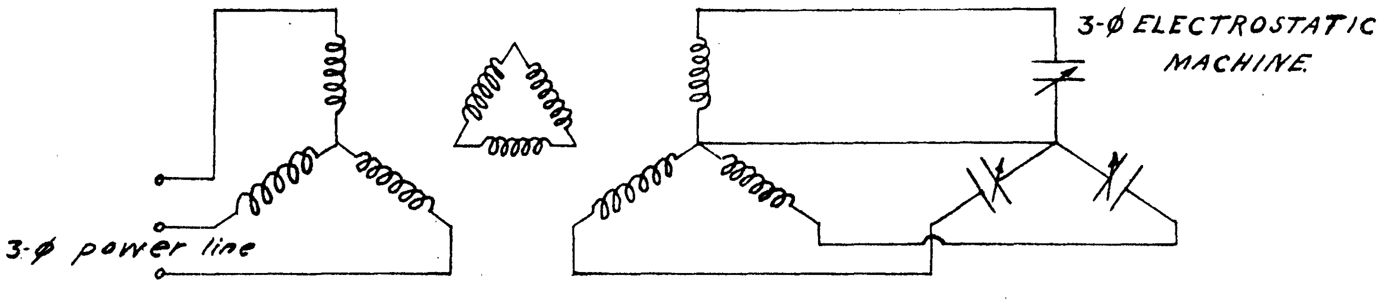


FIGURE 7

VACUUM ELECTROSTATIC MACHINE -- TYPE 2.

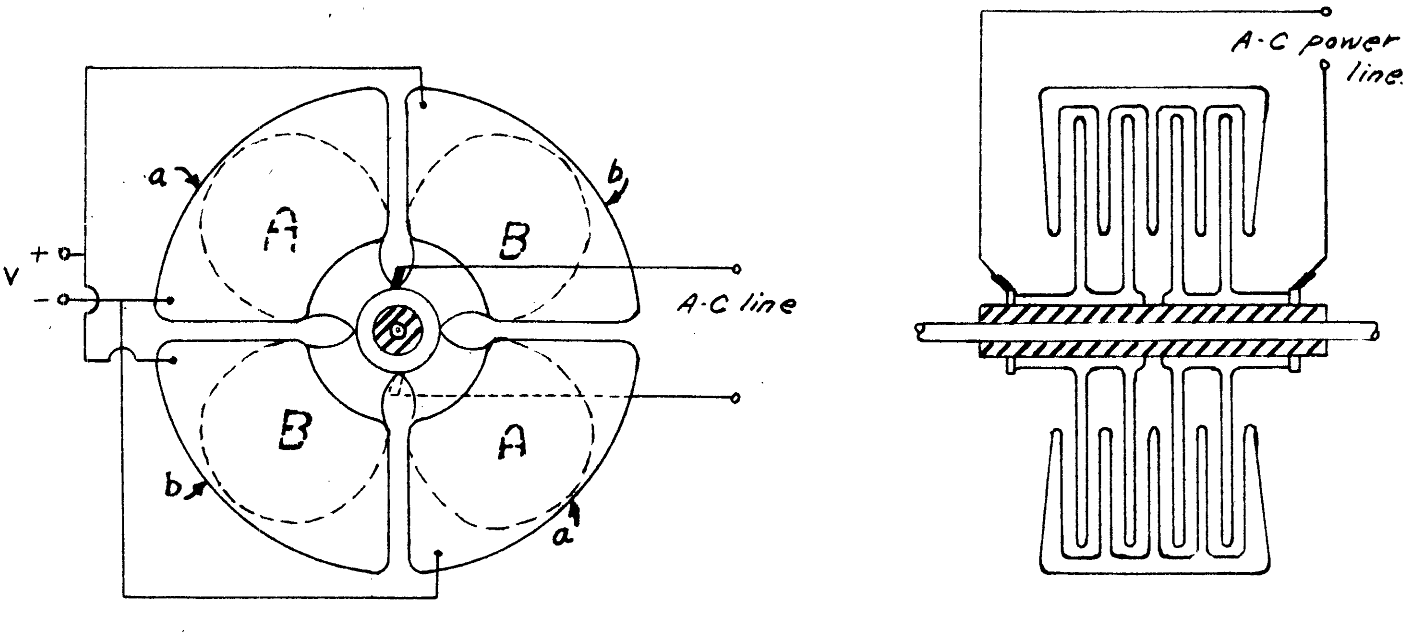


FIGURE 8

SCHEMATIC OF 1-φ MACHINE -- TYPE 2

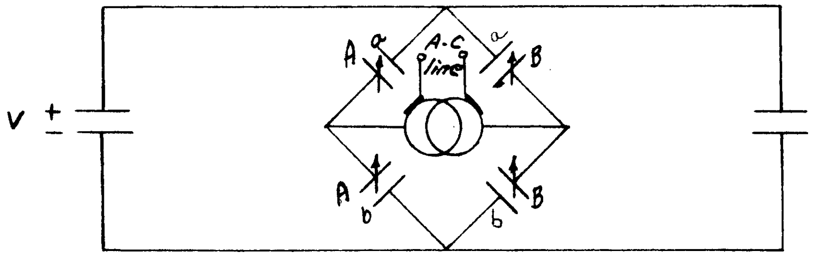


FIGURE 9

SCHEMATIC OF 3-φ MACHINE -- TYPE 2

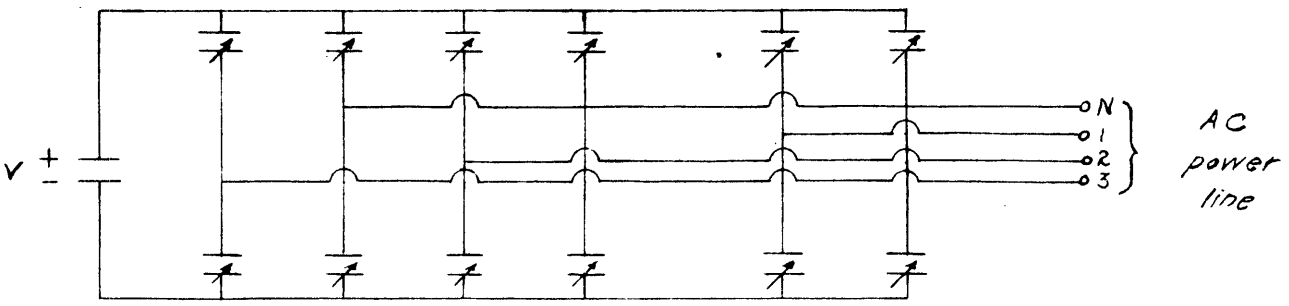


FIGURE 10

VACUUM ELECTROSTATIC GENERATOR.— TYPE 3.

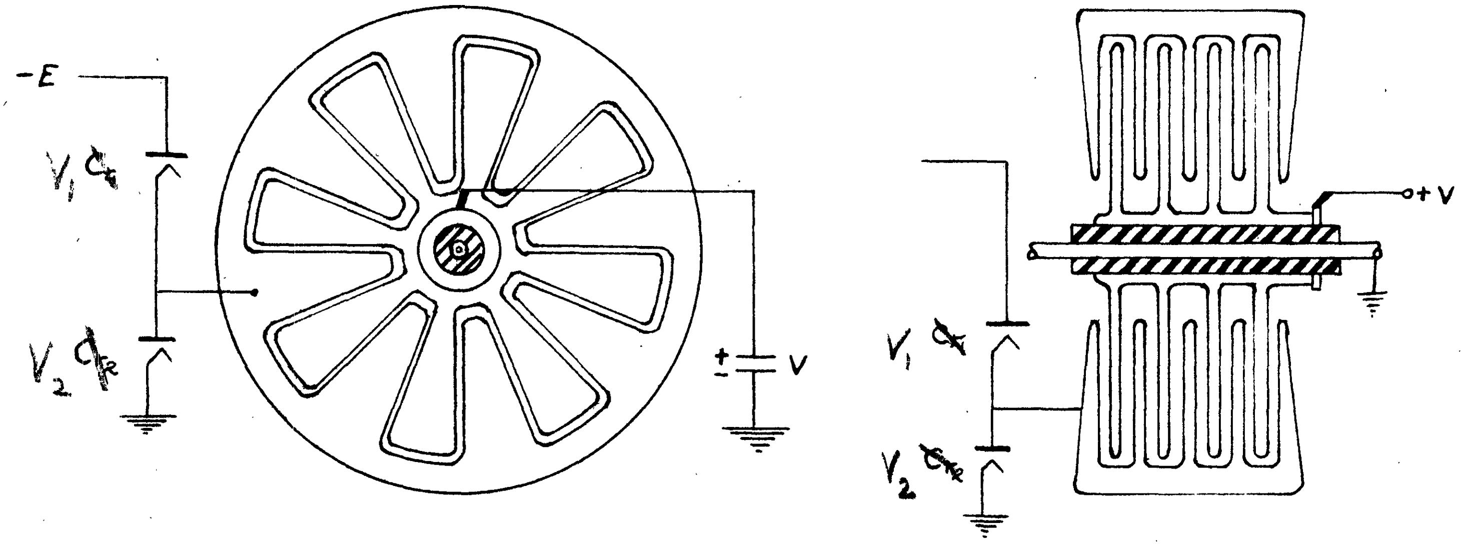


FIGURE 11

SCHEMATIC OF TYPE 3 GENERATOR.

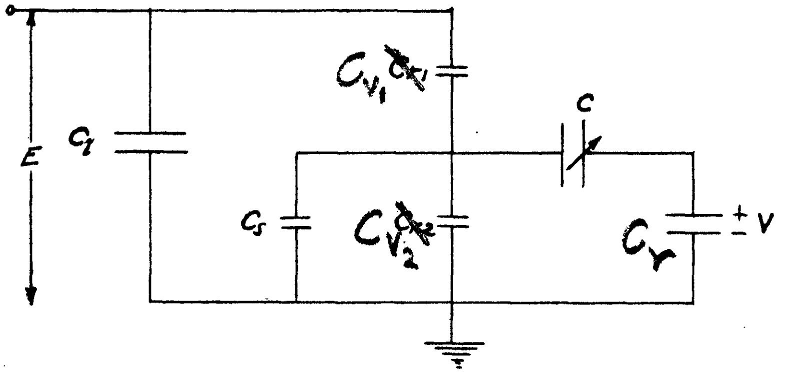
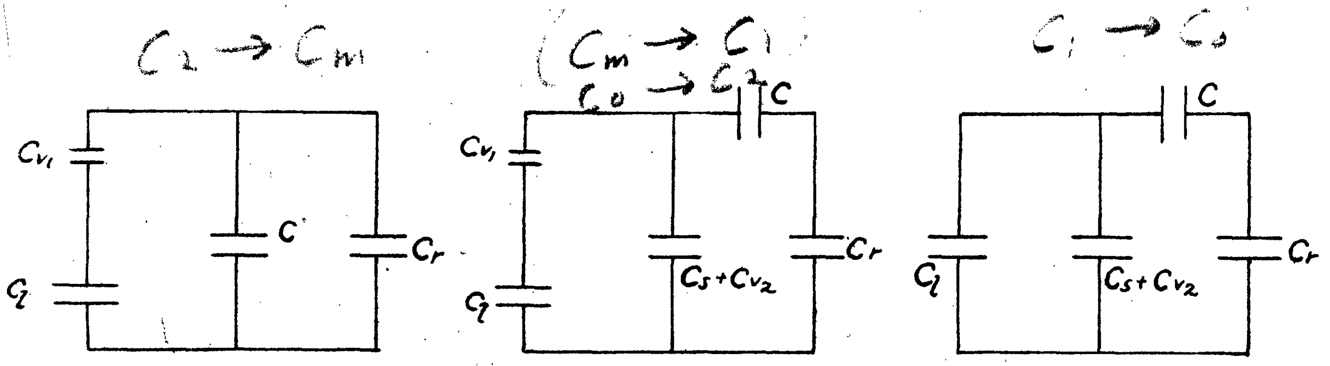


FIGURE 12

CIRCUIT CONNECTIONS DURING CYCLE FOR TYPE 3 GENERATOR.



12-C 12-A 12-B

FIGURE 13

CAPACITANCE VARIATION IN TYPE 3 GENERATOR

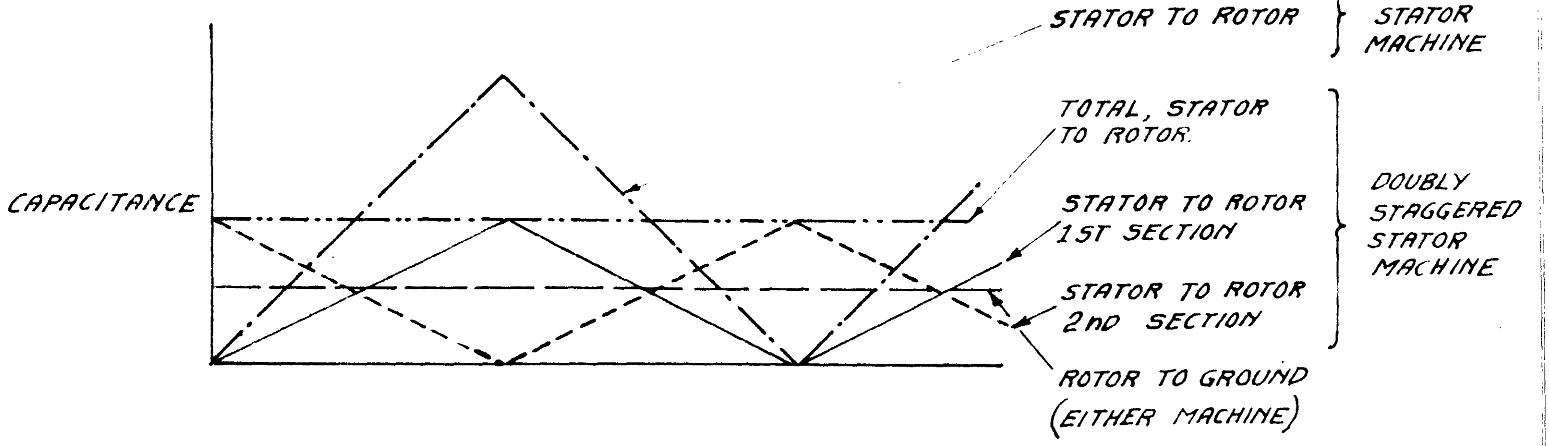


FIGURE 14

VACUUM ELECTROSTATIC GENERATOR - TYPE 4.

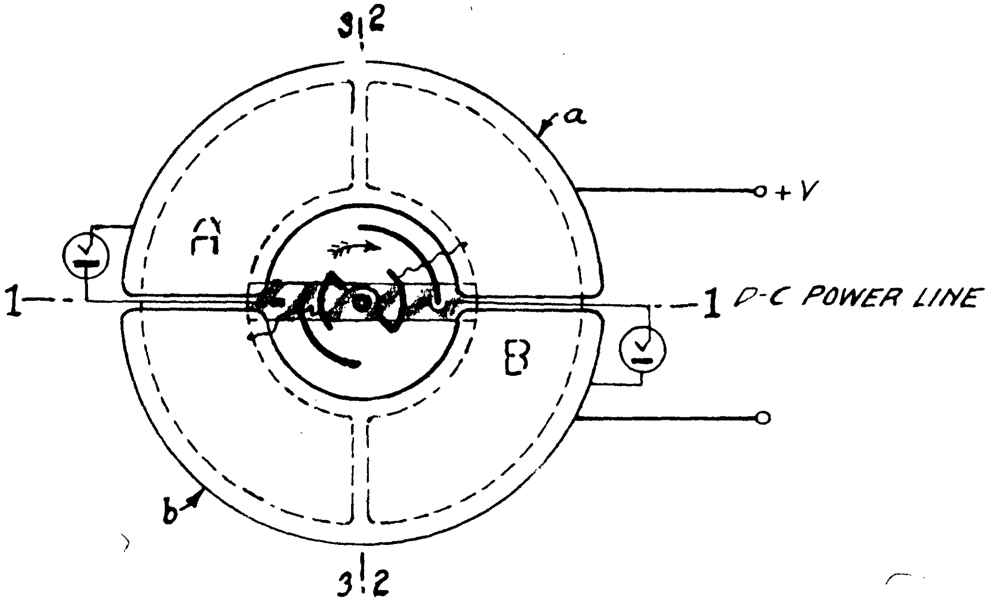


FIGURE 15

TYPE 4 GENERATOR SHOWING PRACTICAL CONSTRUCTION

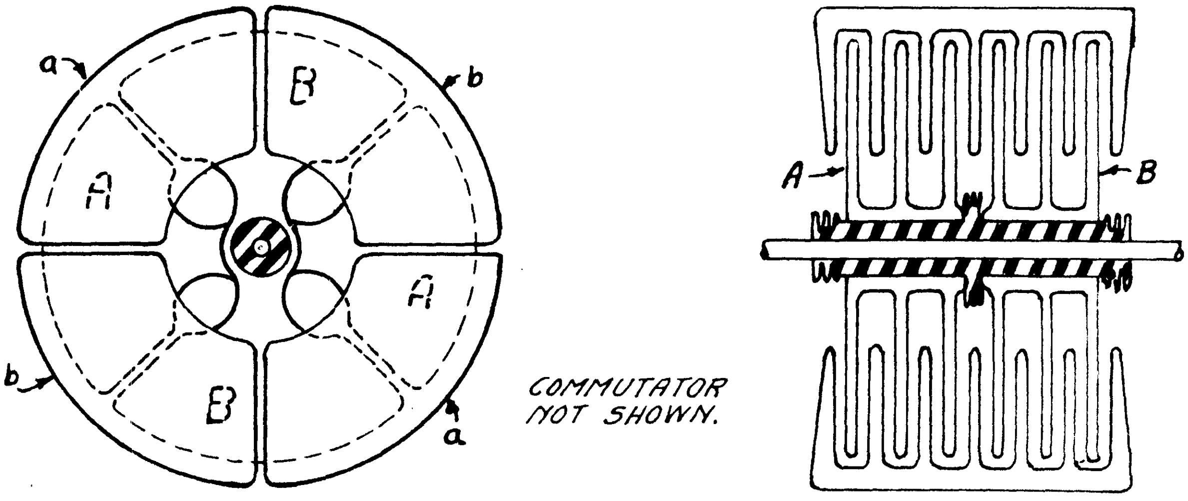


FIGURE 16

VACUUM ELECTROSTATIC GENERATOR--TYPE 5.

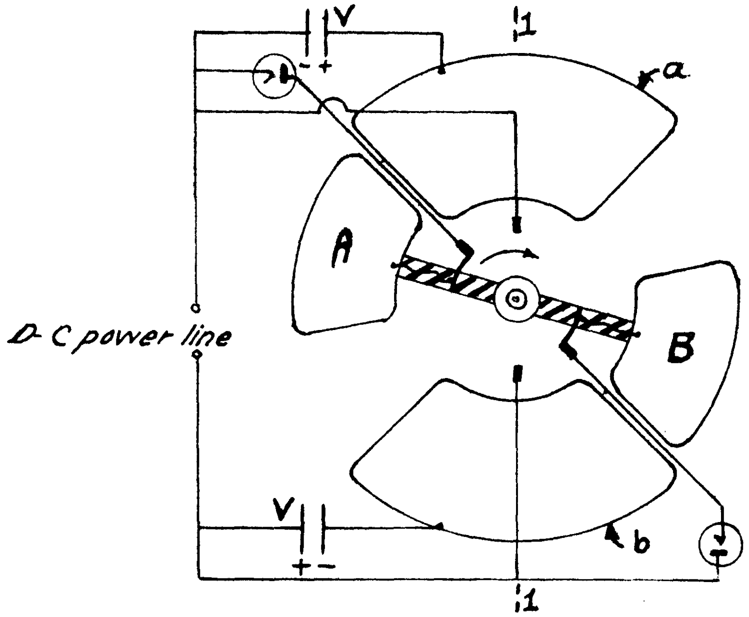


FIGURE 17

TYPE 5 GENERATOR SHOWING PRACTICAL CONSTRUCTION.

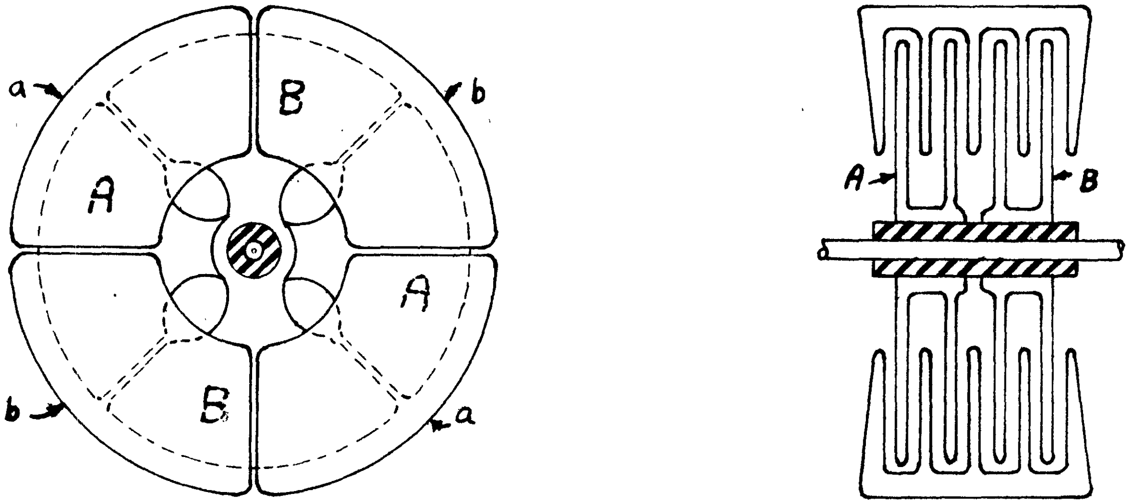


FIGURE 18

VACUUM ELECTROSTATIC GENERATOR--TYPE 6.

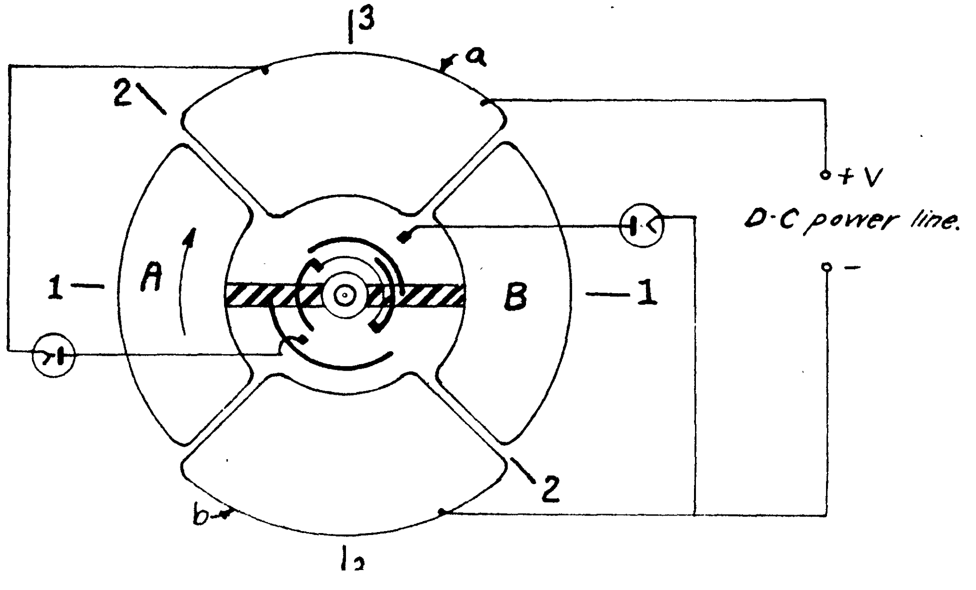
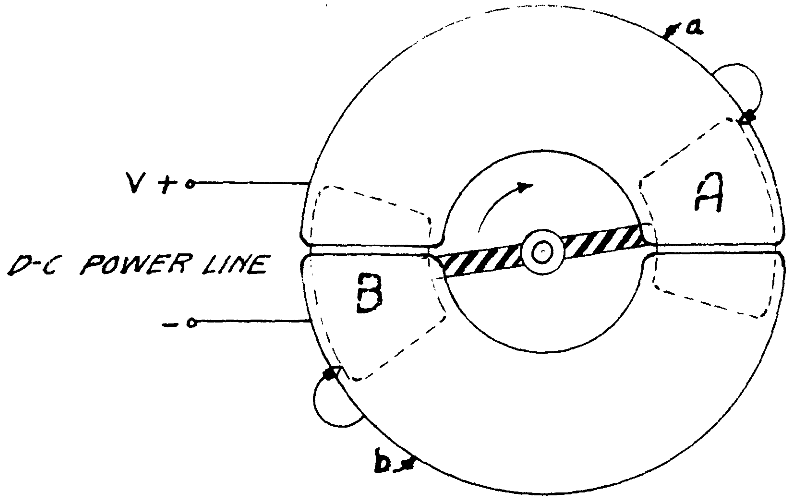


FIGURE 19

VACUUM ELECTROSTATIC MOTOR – TYPE 7



DISCHARGING BRUSHES NOT SHOWN.

FIGURE 20

VACUUM ELECTROSTATIC MOTOR -- TYPE 8.

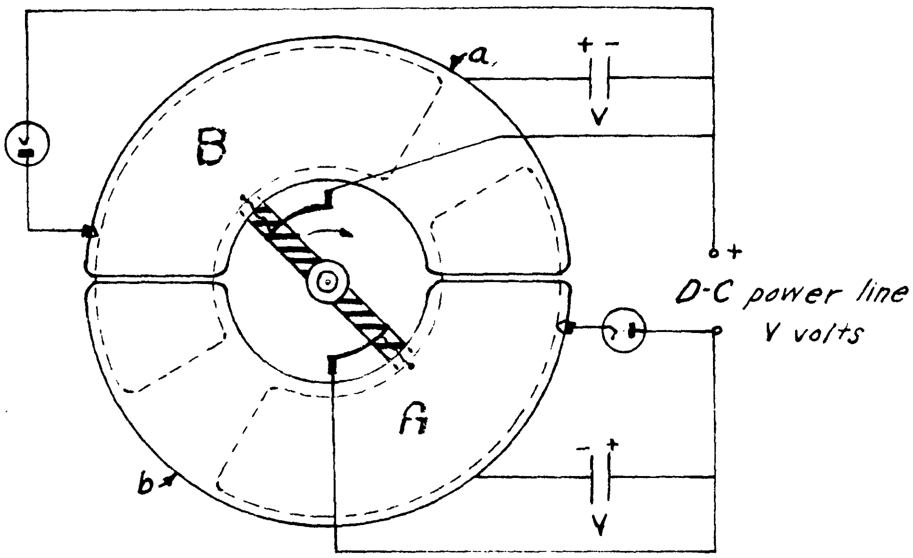


FIGURE 21

VACUUM ELECTROSTATIC MOTOR -- TYPE 9.

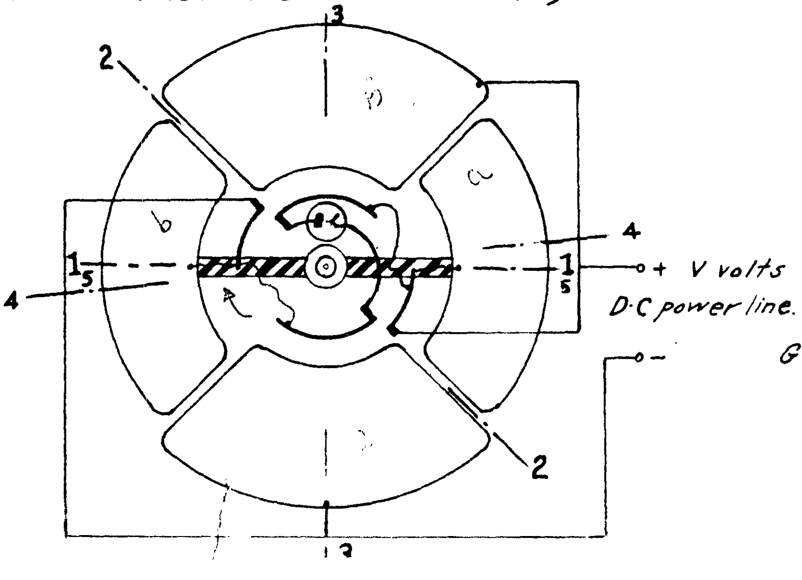


FIGURE 22

POWER CYCLE FOR TYPE 9 MOTOR

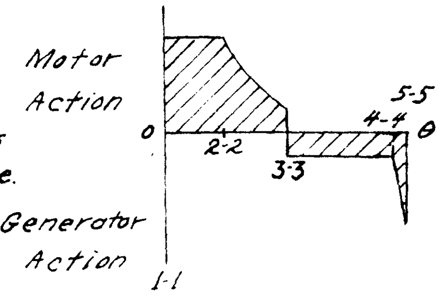


FIGURE 23

TYPE	CLASSIFICATION	MAXIMUM POWER	MAXIMUM ELECTRIC STRESS	POWER CONCENTRATION FOR SAME SIZE AND ELECTRIC STRESS	REMARKS
I FIG. 1	A-C SYNCHRONOUS MOTOR OR GENERATOR LINE EXCITATION	$P = \frac{1.15 \times 10^{-15} nps (r_1^2 - r_2^2) E^2}{d}$ WATTS $n = 120f/p.$	E	1	PROMINENT 3RD HARMONIC. GREAT SIMPLICITY.
II FIG. 7	A-C MOTOR OR GENERATOR SEPARATE EXCITATION	$P = \frac{0.58 \cdot 10^{-15} nps (r_1^2 - r_2^2) V^2}{d}$ $n = 120f/p.$	V	$\frac{1}{2}$	NO HARMONICS.
III FIG. 10	D-C GENERATOR SEPARATE EXCITATION	$P = \frac{4.63 \times 10^{-15} knps (r_1^2 - r_2^2) VE}{d}$ $k < 1$	$E+V$	k	GREAT SIMPLICITY. K VARIES BETWEEN 0.5 AND 0.9 IN PRACTICAL MACHINES.
IV FIG. 14	D-C GENERATOR LINE EXCITATION	$P = \frac{0.58 \cdot 10^{-15} nps (r_1^2 - r_2^2) E^2}{d}$	E	$\frac{1}{2}$	COMMUTATION ANGLE CAN BE MAINTAINED THE SAME AT ALL LOADS.
V FIG. 16	D-C GENERATOR SEPARATE EXCITATION	$P = \frac{4.63 \cdot 10^{-15} nps (r_1^2 - r_2^2) VE}{d}$	$E+V$	1	STRUCTUALLY MORE COMPLEX THAN TYPE III.
VI FIG. 18	D-C GENERATOR LINE EXCITATION	$P = \frac{0.29 \times 10^{-15} nps (r_1^2 - r_2^2) E^2}{d}$	E	$\frac{1}{4}$	NOT RECOMMENDED IN GENERAL.
VII FIG. 19	D-C MOTOR	$P = \frac{4.63 \times 10^{-15} Knps (r_1^2 - r_2^2) E^2}{d}$ $K = \frac{C_1}{C_m} - \left(\frac{C_1}{C_m}\right)^2$	E	$4K$	HAS POWER LOSS EQUAL TO $100 \, C_1/C_m - C_1$ % OF OUTPUT. K SHOULD BE LESS THAN $1/8$.
VIII FIG. 20	D-C MOTOR SEPARATE EXCITATION	$P = \frac{4.63 \times 10^{-15} rnsp (r_1^2 - r_2^2) E^2}{d}$ $r = C_1/C_m \quad V = rE$	$E+V$	r	$r = 1$ FOR MAXIMUM POWER.
IX FIG. 21	D-C MOTOR LINE EXCITATION	$P = \frac{0.58 \times 10^{-15} Knps (r_1^2 - r_2^2) E^2}{d}$ $K = \frac{C_m - 2C_1}{C_m}$	E	$\frac{K}{2}$	K VARIES FROM 0.7 TO 0.9 IN PRACTICAL MACHINES.
X FIG. 24	D-C MOTOR LINE EXCITATION	$P = \frac{0.58 \times 10^{-15} nps (r_1^2 - r_2^2) E^2}{d}$	E	$\frac{1}{2}$	THIS IS PROBABLY THE BEST OF THE LINE EXCITED MACHINES.

P = POWER IN WATTS
n = R.P.M
p = NUMBER OF POLES
s = NUMBER OF ROTOR DISKS.
d = SEPARATION OF ROTOR AND STATOR IN CM.
r_1, r_2 = RADII OF ROTOR IN CM.

FIGURE 24

VACUUM ELECTROSTATIC MOTOR — TYPE 10.

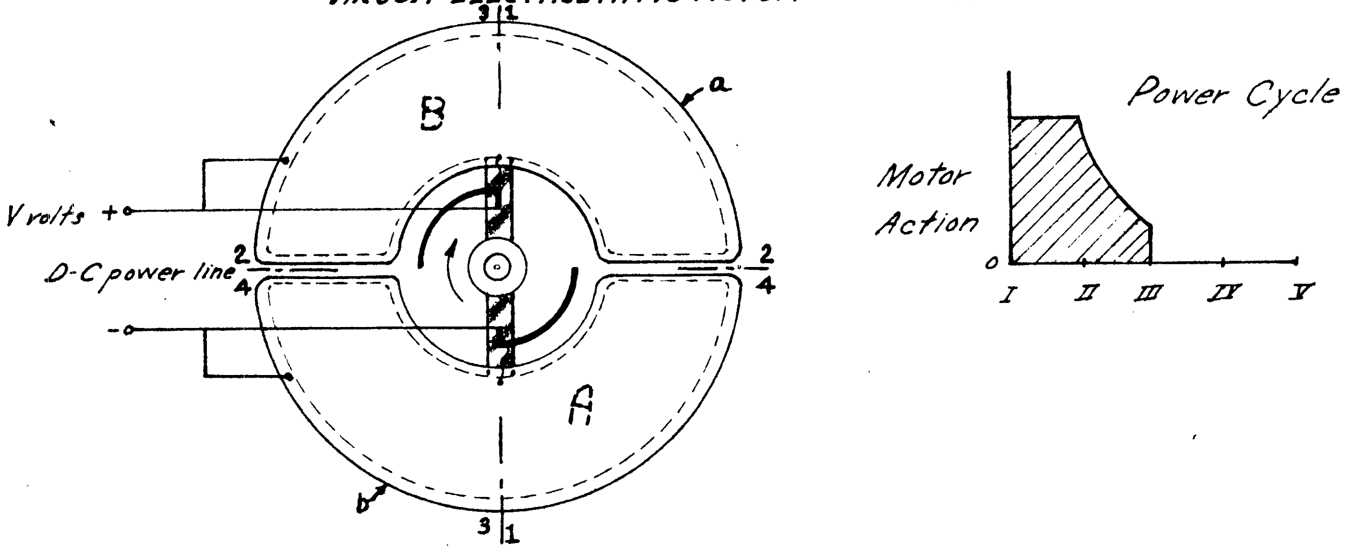
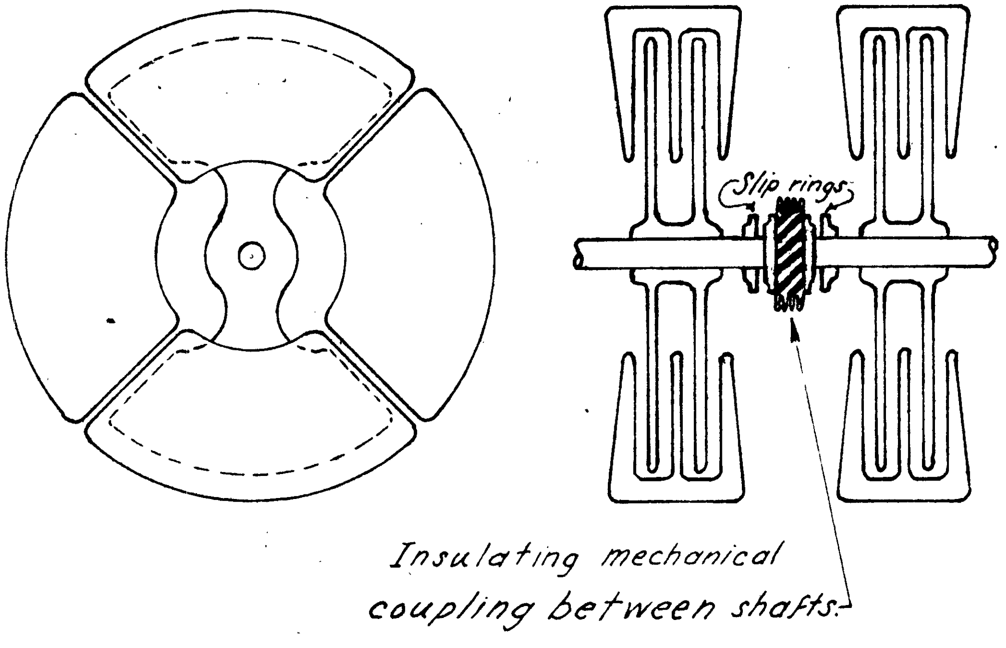


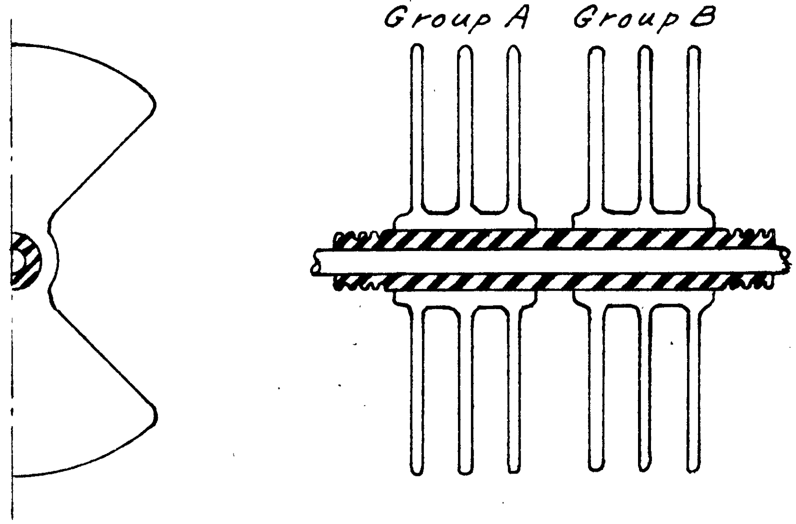
FIGURE 25

PRACTICAL ELECTROSTATIC MACHINE CONSTRUCTION USING SOLID METALLIC ROTOR UNITS.



Views showing solid metallic rotor construction, each group solidly on shaft, with sections of shaft electrically insulated.

Insulating mechanical coupling between shafts.



Section showing separate rotor groups each constructed solidly of metal and insulated from shaft.

CHAPTER III

GENERAL CONSIDERATIONS IN THE DESIGN OF VACUUM ELECTROSTATIC MACHINERY

This chapter is devoted to an analysis of practical aspects of the vacuum electrostatic machinery described in the previous chapter.

A. SOLID METALLIC ROTOR MEMBERS

In the simplified explanations and diagrammatic sketches of the vacuum electrostatic machines described herein, the interleaving rotor members have in general been made up of several metallic sectors in the same plane but performing different functions and hence insulated from each other. In an actual machine such non-integral rotor construction, though often resulting in higher power concentration, would involve serious mechanical difficulties. It is an important idea that all electrostatic machines can be designed so that the sectors in each separate rotor member perform at the same time the same function and therefore exist always at the same potential relative to one another. Hence each rotor member with its plurality of poles can be made as a metallic unit with consequent great increase in mechanical strength and simplicity. The rotor members which perform different functions are displaced along the shaft and properly insulated from it and each other. The necessary connections between rotor members performing different functions during the cycle may be made through slip rings or some equivalent arrangement. Each group of rotor members performing simultaneously the same function may be assembled as a unit and insulated from the shaft, or mounted solidly on an insulated section of the shaft. Some of these ideas are illustrated in Figs. 15, 17, and 25.

B. METHODS OF SECURING CAPACITANCE VARIATION

The electrostatic machines described herein are, as has been stated, essentially variable condensers or combinations of such simple variable condensers. Various methods for securing capacitance variation suitable for electrostatic power machinery are outlined below. These methods may be used either separately or in combination.

(1) Flat parallel-plate interleaving rotor and stator members.

   a. Segmented circular plates illustrated in Fig. 26(a).
   b. Segmented non-circular plates illustrated in Fig. 26(b).

(2) Flat interleaving rotor and stator members with progressively-varying separation.

   a. Stator plates whose thickness varies with angle, Fig. 26(c).
   b. Rotor plates whose thickness varies with angle.

(3) Corrugated interleaving rotor and stator members as in Fig. 27.

(4) Cylindrical interleaving variable condensers as in Fig. 26(d).

These methods of securing capacitance variation between rotor and stator are general. The illustrative sketches are intended only to bring out the ideas involved and not the particular form by which these ideas can be realized.

C. UNBALANCED ELECTROSTATIC FORCES AND RESONANCE

It is evident that when the rotor is symmetrically interleaved with the stator the axial electrostatic forces acting on the interleaving rotor and stator members (except the two outer stator members) are exactly outbalanced. Any displacement of the rotor from axial symmetry with the stator results in an axial force tending to bend both rotor and stator poles. If d is the separation between rotor and stator surfaces when symmetrically disposed, and x the displacement of the rotor from this symmetrical position, then the ratio of the unbalanced axial force acting on the displaced rotor to the force acting on one face of the rotor when centrally located is

$$R = \frac{4d^3x}{(d^2-x^2)^2} \qquad \text{where} \quad x < d \qquad (101)$$

When $x = 0.23d$ this ratio is unity. The importance of proper symmetrical disposition of the rotors between the stators, is thus shown. The two end stator plates must be designed to withstand the full unbalanced axial force developed on the inner faces.

During the operation of vacuum electrostatic machinery slight unsymmetry between rotor and stator results in periodic electrostatic force tending to deflect the rotor and stator blades. The frequency of these periodic forces is given by

$$f = \frac{np}{60} \qquad (102)$$

and at certain speeds will be closely equal to, or a multiple of, the natural frequency of the pole structure. When this resonance situation obtains, the pole structures will tend to vibrate with relatively large amplitudes. This would result in further unsymmetry and hence still greater unbalanced electrostatic forces, and lead conceivably to either electrical or mechanical failure or both.

In the design of electrostatic machines the rotor and stator structures must have sufficient rigidity to overcome the effects of slight unsymmetry, and the choice of operating speed and number of poles must be so related to the natural pole frequency that resonance is avoided. The natural frequency of the poles in a large machine will necessarily be low compared with the forced vibration, and the possibility of resonance due to harmonic frequencies must be carefully considered. In the tapered construction the cantilever beam constituting the poles is thickest at the fixed end - an arrangement capable of high rigidity. The construction suggested in Fig. 27 is also evidently highly desirable from this point of view.

D. COMMUTATION

The problem of establishing the necessary electrical connections between the rotor and stator members of direct-current-vacuum electrostatic-power machines can be met in a number of ways. Some of these will be treated briefly in the following discussion.

1. Mechanical Commutation

It has been emphasized in the machine theory that in all cases the necessary electrical connections during a power cycle can be established at intervals when zero voltage exists between the approaching commutator sections. It has also been brought out that the necessary electrical disconnections can always be effected at times of zero-current flow. Both for electrical connections and disconnections it is desirable that the voltage between the approaching or departing commutator contacts be less than the breakdown voltage at any instant. This idea is illustrated in Fig. 28(a). It is desirable that the contactors have large areas of contact, that they are not subject to sliding friction, and that the commutator timing elements are readily accessible. A commutator arrangement which realizes these requirements is illustrated in Fig. 28. The control disk which actuates the contactor revolves synchronously with the power machine. It is located in the atmosphere, the link movements being transmitted mechanically into the vacuum chamber through a vacuum-tight seal. The followers on the control disk are readily accessible and are designed for fidelity of operation and long life. The contactors themselves are of material chosen for the high insulation strength resulting from their surface properties. The spring and stop arrangement, and the spring tension and mass of the system are designed to produce great rapidity in connection and separation of the contactors and to avoid excessive mechanical forces.

2. Mechanical and Electronic Commutation in Direct-Current Machines

While for any fixed load condition the optimum angle of commutation remains constant, variation of output voltage or current will in general change the location in the cycle at which the optimum conditions for commutation are realized. In the types IV and VI generators, however, the optimum commutation angle is the same for all conditions, provided the power is controlled by the methods described in Chapter II, D, 4(b) and 4(c). For these generators, therefore, the problem of mechanical commutation is relatively simple. For the types III and IV generators a combination of mechanical commutator with an electronic valve arrangement in series may be used to enforce the transference of charge under the optimum conditions. This applies also to the various direct-current motors whose theory has been disclosed. In general these valves perform the functions of kenotrons. For positive power control these valves may be used as switches in the manner suggested in Chapter II. The theory of such switches and valves is discussed in Chapter VIII.

E. POWER CONCENTRATION

The relative power concentrations of the various direct-current and alternating-current vacuum electrostatic machines were discussed in Chapter II. The following calculation enables a comparison of the power concentration of vacuum electrostatic power machines and of modern electromagnetic power machines. In this calculation it is assumed that ultimately vacuum electrostatic machines can withstand operating voltages of 1,000,000 volts and operating gradients of 2,000,000 volts per centimeter.

The formula for the maximum power developed by the Type III separately-excited generator is

$$P = \frac{4.63 \times 10^{-15} \, Knps(r_1^2 - r_2^2)VE}{d} \text{ watts} \tag{70}$$

The following design constants are chosen for the purposes of this illustration.

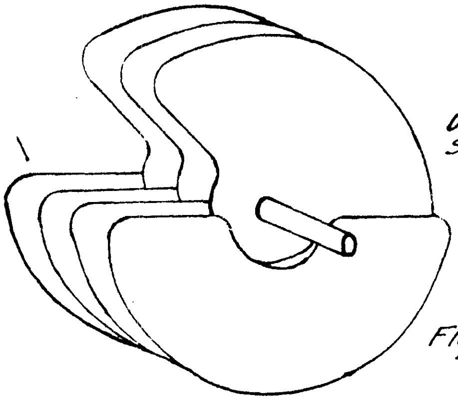
n = revolutions per minute	= 4000
p = number of rotor poles	= 16
s = number of rotor disks	= 50
r_1 and r_2 = external and internal rotor radii in centimeters	= 90 and 30
d = separation between rotor and stator in centimeters	= 0.5
V = rotor inducing voltage	= 500,000
E = rotor line voltage	= 500,000

$$K = 1 - \frac{C_o(E+V)+(C_s+C_{V2})E}{C_mV} = 0.8$$

The maximum power of which this machine is capable under the above conditions is approximately 42,000 kw. The physical size of such a generator would be approximately a cylinder 8 ft. in diameter and 12 ft. long.

What further increases in voltage and voltage gradient insulation strength in vacuum result from technical advances in the art, will be reflected in increased compactness over that suggested above. While exact comparisons of the relative compactness of vacuum electrostatic and electromagnetic power machines must necessarily await the determination of the practical insulation limitations of high vacuum, it seems reasonable at the present time to predict that vacuum electrostatic machines are ultimately capable of greater compactness, lightness and lower cost than is now realized in modern electromagnetic machines.

METHODS OF CAPACITANCE VARIATION.



UNI-SECTOR ROTOR SHOWN FOR SIMPLICITY.

Figure 26a

SEGMENTED CIRCULAR PLATES

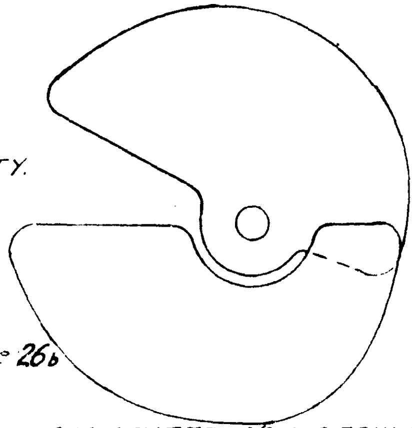


Figure 26b

SEGMENTED NON-CIRCULAR PLATES

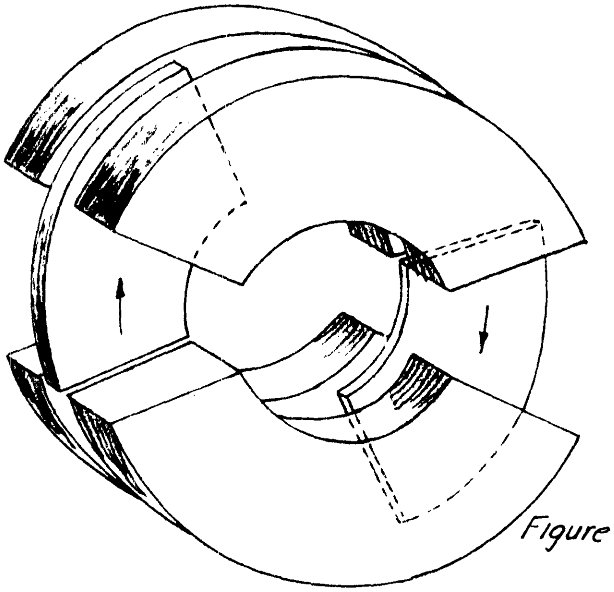
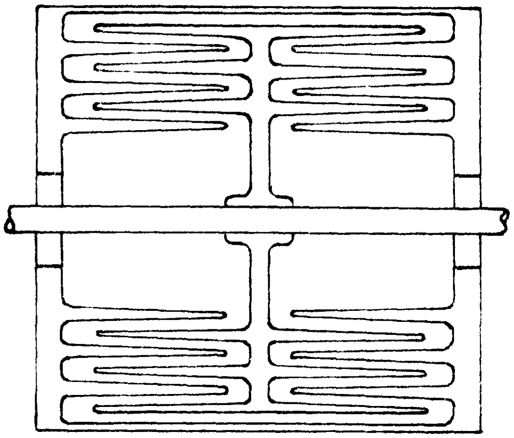


Figure 26 c

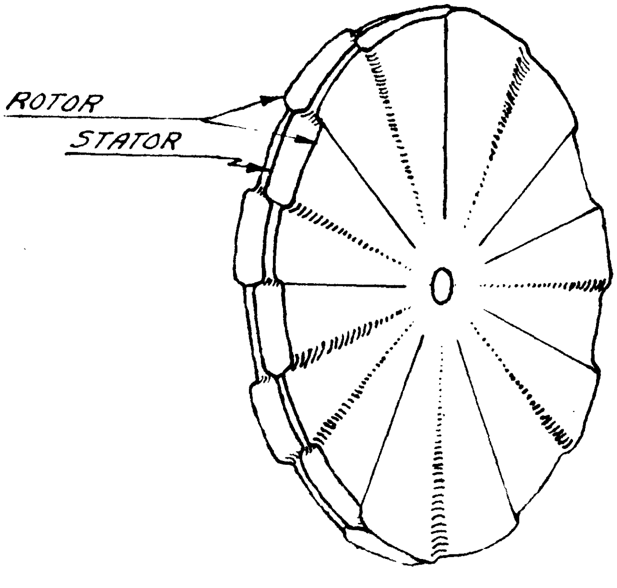
VARYING PLATE SEPARATION

Figure 26-d



CYLINDRICAL INTERLEAVING PLATE CONDENSER

FIGURE 27



CORRUGATED PLATE CONDENSER.

RIM REMOVED.

MECHANICAL COMMUTATOR

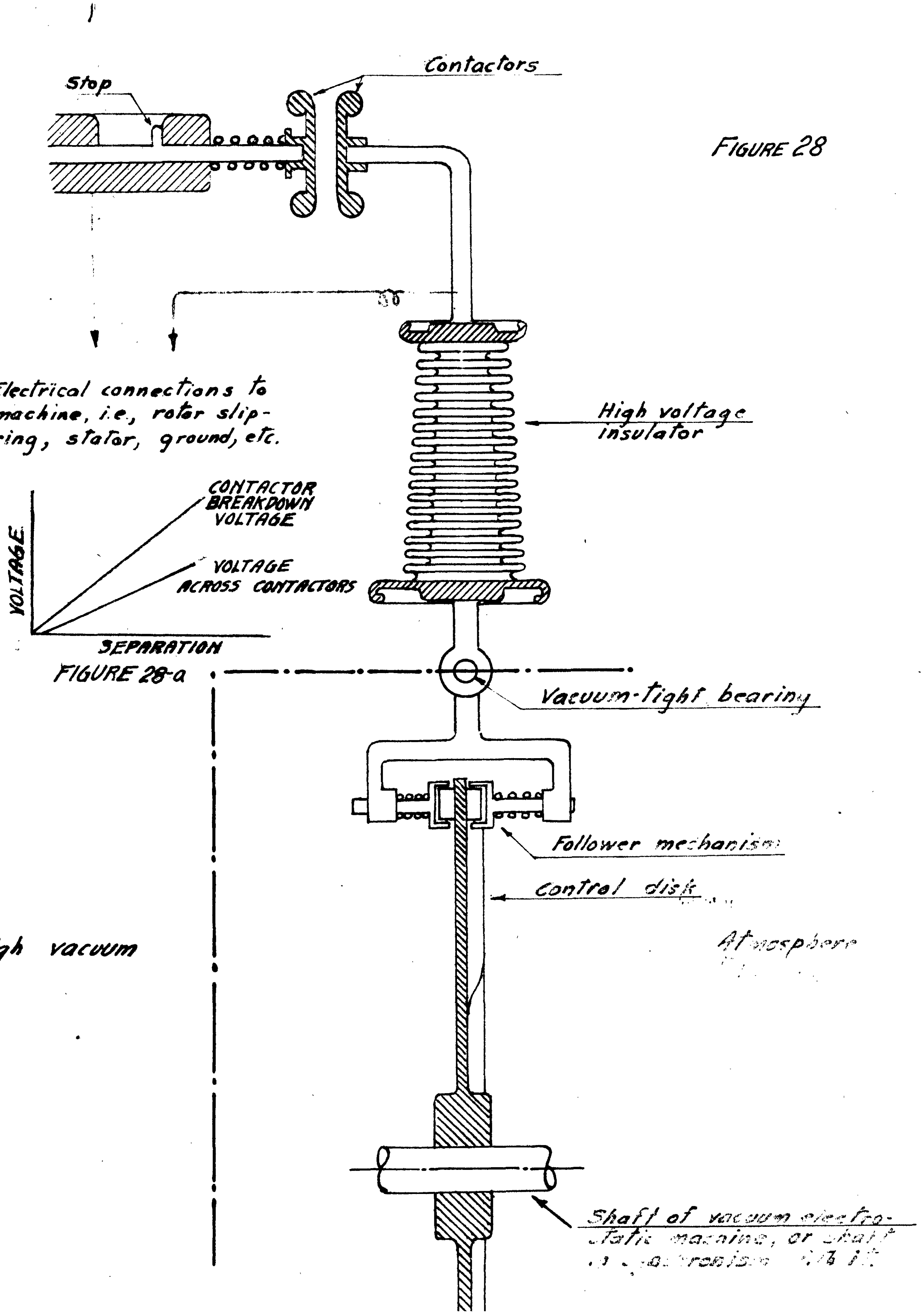


FIGURE 28

FIGURE 28-a

CHAPTER IV

EXPERIMENTAL STUDY OF VACUUM ELECTROSTATIC POWER MACHINES

It became apparent some time after this research was begun that while considerable theoretical evidence of the possibilities and importance of vacuum electrostatics was already built up, there existed no supporting experimental evidence of any kind. Accordingly an experimental program was undertaken to establish as far as possible the correctness and the practicality of the power applications of vacuum electrostatics. This chapter deals with the experimental work on vacuum electrostatic machines performed during this research.

1. Study of Voltage Gradients at Electrode Surfaces

In the chapter on machine theory it was made evident that the power developed by a given machine is proportional to the highest operating voltage gradient between the faces of the rotor and stator plates. The voltage gradient between the approaching edges of the interleaving stator and rotor plates may be considerably higher than the maximum operating gradient, and hence plays an important part in preventing the effective utilization of the full gradient insulating strength of electrodes in vacuum. Since electrostatic machines of large power capacity require the interleaved-plate type of construction, the problem of properly shaping the edges of the plates is of fundamental importance, and an auxiliary study of this was undertaken.

The configuration of the edges of the plates of an electrostatic machine is too difficult to be handled readily by analytical methods. Graphical flux plotting is too liable to error to be very useful in showing the effect of small changes in the shape of the edges. The desire for an accurate and flexible experimental arrangement led to the rejection of standard methods of gradient determination and the development of a new null method which is described in Appendix B.

The gradient distribution along the edge and sides of a typical plate in an interleaving arrangement of plots for various separations between the approaching rotor and stator edges was experimentally determined. Fig. 29 gives the family of curves for circular-edged plates, showing the variation of the gradient distribution around the contour as the rotor and stator plates move from a separated position to a well-interleaved position. If the separation between the parallel surfaces of the interleaved plate is taken as unity, the thickness of the plates was 0.635, and the range of movement was from +7 (separated) to -14 (interleaved). It is seen that with the circular-edged plates the voltage gradient at the most unfavorable position is not localized but quite uniform over the edge. This indicates that the circular contour is very nearly the optimum contour for the plate edges. Since the voltage gradient at a metallic surface is a function of its curvature, another study was made and a second family of curves obtained for interleaving rotor and stator plates with circular bulbous edges. These results are given in Fig. 30. It is seen that the increased curvature has reduced the gradient at the tips, but that this effect has been compensated at the sides of the bulge by the reduced separation when the rotor and stator bulges are passing each other.

Some of the significant data from these curves are tabulated below for convenience:

Ratio of plate thickness to plate separation = 0.635

Ratio of diameter of circular bulge to plate separation = 0.873

Ratio of maximum edge gradient to the face gradient for the circular-edged plates = 1.79
for the bulbous-edged plates = 1.77

Ratio of maximum tip gradient to the face gradient for the circular-edged plates = 1.69
for the bulbous-edged plates = 1.59

The fact that the ratio of the maximum gradient at the edges to the gradient between the parallel faces of the interleaved plates was closely the same for both the circular-edged and the bulbous-edged plates indicates that at this particular ratio of plate thickness to plate separation, namely, 0.635, both contours show equal advantage. For ratios of plate thickness to separation which are greater than 0.635 the circular-edged plate is decidedly the most advantageous; for ratios less than 0.635 the bulbous-edged plate becomes most favorable. These tendencies are made more readily apparent by considering the extreme cases of thick plates and relatively negligible spacing, and then large spacing with extremely thin plates.

2. Test of Synchronous Vacuum Electrostatic Machine - Type I

A small electrostatic machine for operation in high vacuum as a synchronous motor or generator, Type I, was built and tested during this investigation. This machine is shown in Figs. 33 and 34 on the end plate of the experimental vacuum tank, with the tank rolled away.

The plates were made of 1/4" sheet aluminum with circular edges. The separation rotor to stator was one centimeter, the outer diameter of the rotor was 13 1/2" and the inner diameter 1 3/4". The stator poles were sector-shaped and the rotor poles so shaped that, neglecting end effects, the rate of capacitance variation between rotor and stator was sinusoidal.

The rotor was maintained at ground potential and the stator insulated from ground by six 4-inch Isolantite stand-off insulators. The high-voltage alternating-current power lead was brought into the tank through the pyrex-pipe bushing from a bank of three 22,000-volt potential and primary-regulator transformers connected as shown in Fig. 31. The two-pole design and the 60-cycle power frequency fixed the synchronous speed of the machine at 3600 r.p.m.

A separate driving mechanism for bringing the electrostatic machine up to synchronous speed as a motor, or for driving it as a generator, was provided. The auxiliary driving motor was mounted outside the tank and its power carried into the vacuum tank by means of a vacuum-sealed shaft. An arrangement was made, using two of the vacuum-tight controls on the tank whereby the driving mechanism could be uncoupled from the electrostatic machine while in operation, leaving it entirely free in vacuum, subject only to the friction of its ball bearings.

A neon bulb, connected to the alternating-current supply, was mounted inside the tank for the purpose of indicating, by its stroboscopic action, when synchronous speed was attained. A small 60-cycle Edgerton stroboscope was mounted just outside the lead-glass window in the face plate for the purpose of illuminating a graduated power-angle disk connected to the rotor within.

A small prony brake consisting of a baked asbestos band passing over the electrostatic motor shaft and tightened by springs at each end operated by two control shafts was also provided. The springs carried scales which could be observed through the window so that the spring tension during load runs could be accurately determined and recorded.

The machine was later equipped with a mechanical damper for the purpose of damping out its power-angle oscillations, an interesting characteristic of electrostatic power machinery being the complete absence of such damping action as is so advantageously furnished by eddy-currents in electromagnetic machinery.

The vacuum system was as described in Chapter V and as shown in Figs. 33 and 34, and was producing regularly an operating vacuum of about 10^{-5} mm. Hg. or better. The pumping system consisted of a 55-liter-per-second mercury diffusion pump backed by a Cenco Hypervac. A metal CO_2 condensation trap in series with the mercury pump and tank, and a re-entrant liquid-air trap took care of the condensable vapors.

The vacuum electrostatic machine described above operated successfully as a synchronous motor for the first time on August 9, 1933, delivering useful power to the outside of the tank for over an hour. It is believed that this is the first successful vacuum electrostatic power machine. During subsequent tests it was also run as a high-voltage alternating-current generator delivering useful power back to the line.

The maximum power developed by this machine as a motor with an applied peak voltage, as measured between sphere gaps, of 73 kilovolts, was 55 watts. Its maximum power output as a high-voltage alternating-current generator was closely the same. The theoretical maximum power of this machine operating on sinusoidal impressed voltage of 73 kilovolts peak is only 39 watts. The theoretical maximum power operating on a rectangular wave of voltage of the same maximum amplitude is 78 watts. It was definitely known that the wave-shape of the impressed voltage was not sinusoidal but quite rectangular due to the impedance of the transformers coupled with the strong third harmonics in the magnetizing circuits and in the load. The experimentally-determined value for the maximum power output of the machine, therefore, checks very well with the theoretically-approximated value.

The variation of power output with power angle was experimentally determined for both generator and motor operation. The power-versus-power-angle curve for a peak-voltage value of 73 kilovolts is given in Fig. 32. The maximum theoretical power angle is ± 45 degrees. Although this maximum power angle was observed during test, the presence of small oscillations in the region of pull-out prevented any accurate determinations of power for power angles beyond 35 degrees. The observed power-angle variation agreed with the theory given in Chapter II.

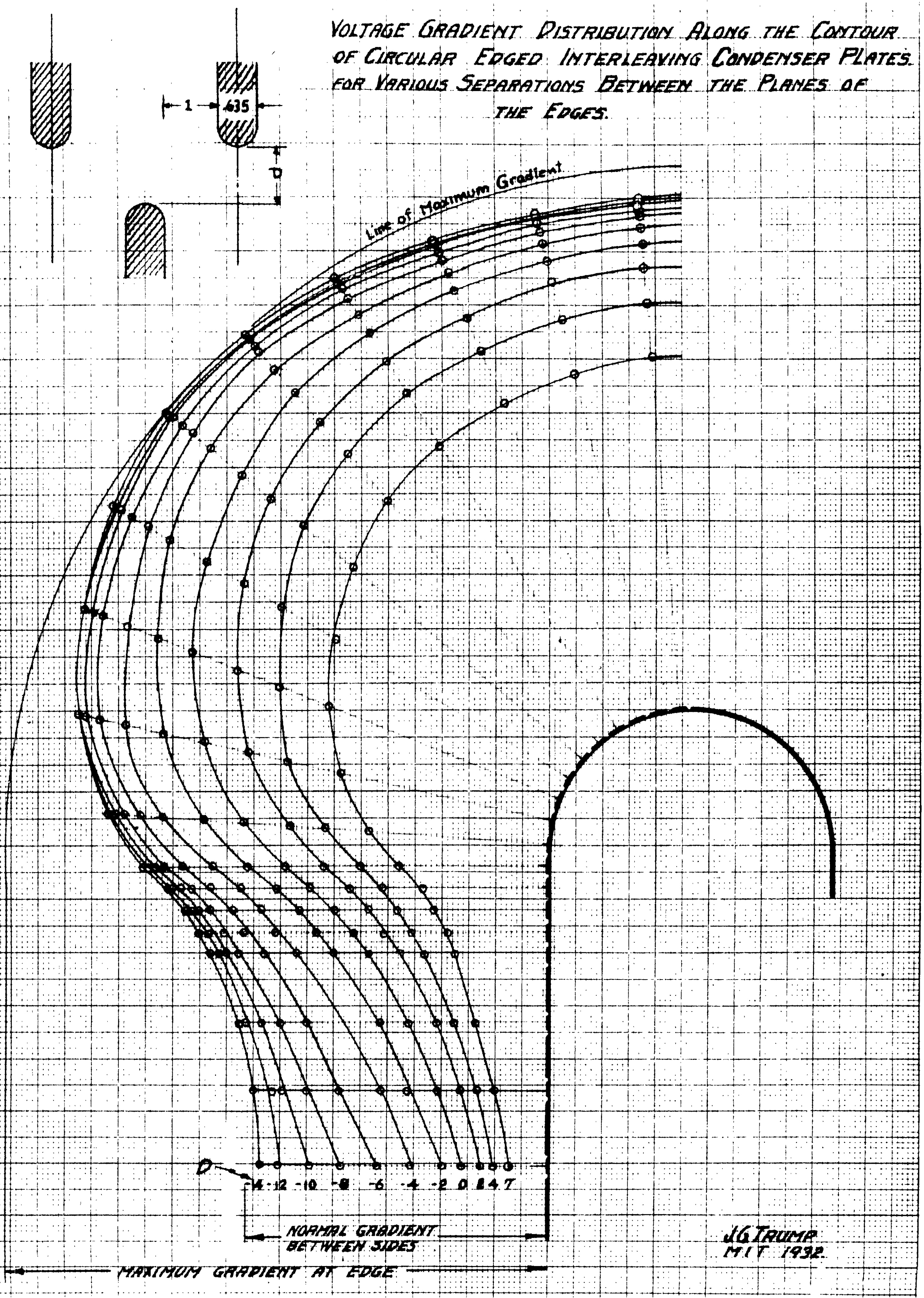
A retardation test was made to determine the power loss due to friction of the bearings. This loss was found to be less than 0.3 watt at 3600 r.p.m. The windage loss and the I^2R loss due to charging currents may be taken as zero. The loss through the volume of the insulators supporting the stator is again zero, the volume resistance stator to ground being of the order of 10^{13} ohms. The surface leakage along the insulators, which in a better design could be made zero, is estimated to have been (for considerable intervals) of the order of one microampere. The efficiency of the vacuum electrostatic motor at full load was therefore somewhat better than 99 per cent. It is evident that in larger machines of this type higher efficiencies can be realized.

The purpose of this experimental study of a vacuum electrostatic power machine was to establish experimentally the correctness of theory of such machines, to illustrate their remarkable simplicity as contrasted with electromagnetic machines, and to develop and demonstrate the means whereby the necessary operating conditions for such machines can be reliably and effectively produced. It was not intended, nor would it be warranted at this time, to carry out intensive and refined tests to exhaust the peculiarities of this particular machine, nor was the machine designed to compete in power concentration with the present highly-developed electromagnetic machines.

This experimental machine study succeeded in all it set out to do. The synchronous vacuum electrostatic machine was operated as both a motor and a generator, exhibited characteristics of reliability and ruggedness in continuous-load runs, developed fully the amount of power for which it was designed, at an efficiency better than 99 per cent. Its construction was characterized by remarkable simplicity and mechanical ruggedness, the only rotating part was constructed entirely of metal and maintained at ground potential, the stator and rotor assemblies were made essentially of suitably-shaped flat metal sectors. The methods of producing the necessary vacuum conditions, of controlling the machine operation, of making measurements and observations resulted in a high degree of flexibility, speed, and reliability. On one occasion the vacuum tank was exhausted from atmospheric pressure to a pressure less than 3×10^{-5} mm. Hg. and the motor brought up to speed and synchronized in 45 minutes. The tests made on the machine check, within the precision of the experiment, the machine theory developed in the theoretical analysis. The measured power output of the machine, regarded in the light of the higher voltage gradients and voltages which it has already been experimentally established can be insulated in vacuum, indicates that power concentration comparable with that of modern alternating-current machines could be realized at once in a new design of the same physical dimensions. Such further advances in vacuum insulation as can confidently be anticipated as the result of vacuum-insulation research should carry the power concentration of vacuum electrostatic power machines far beyond that of modern electromagnetic machines.

FIGURE 29

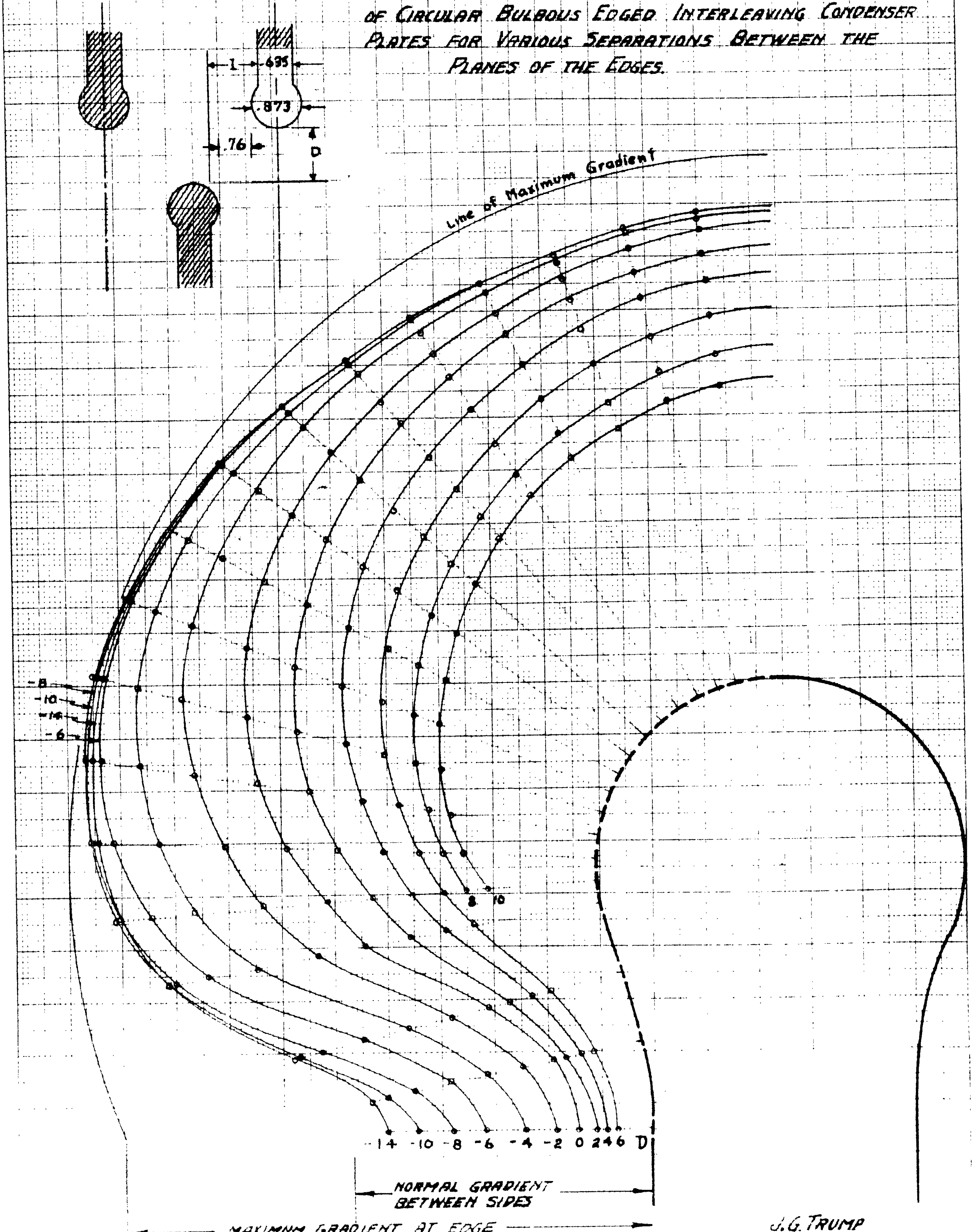
VOLTAGE GRADIENT DISTRIBUTION ALONG THE CONTOUR OF CIRCULAR EDGED INTERLEAVING CONDENSER PLATES FOR VARIOUS SEPARATIONS BETWEEN THE PLANES OF THE EDGES.



J.G. TRUMP
MIT 1932

FIGURE 30

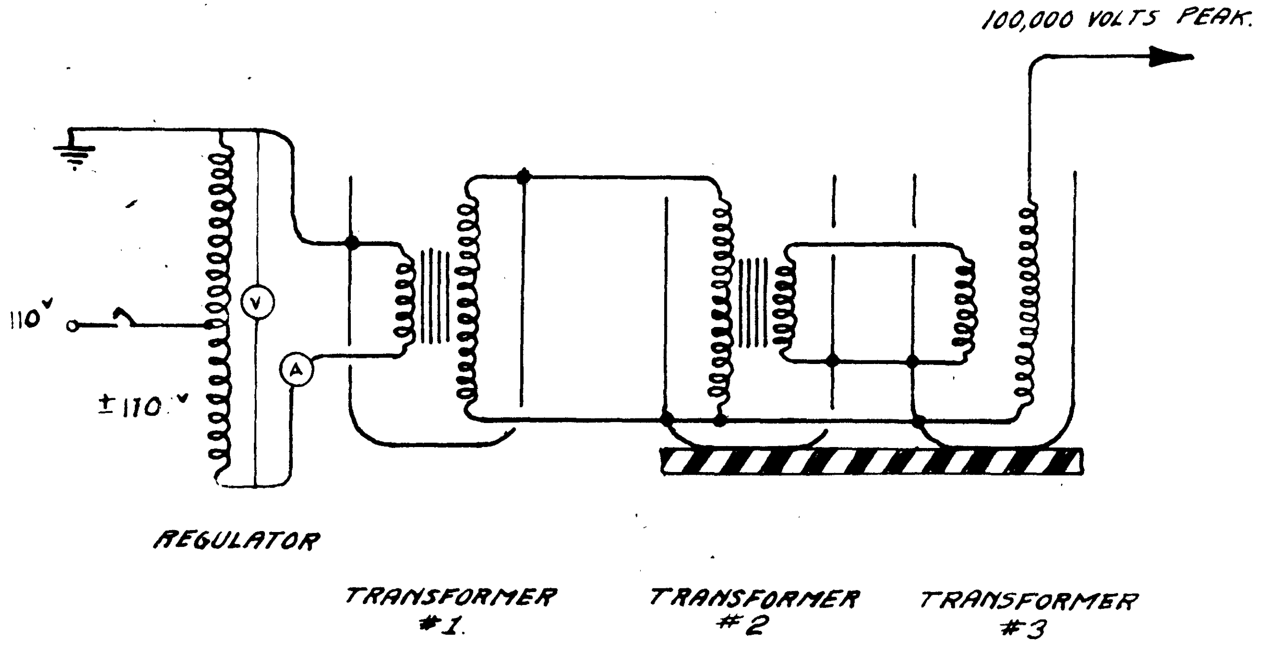
VOLTAGE GRADIENT DISTRIBUTION ALONG THE CONTOUR OF CIRCULAR BULBOUS EDGED INTERLEAVING CONDENSER PLATES FOR VARIOUS SEPARATIONS BETWEEN THE PLANES OF THE EDGES.



J.G. TRUMP
MIT 1932

FIGURE 31

HIGH VOLTAGE TRANSFORMER
SET-UP.

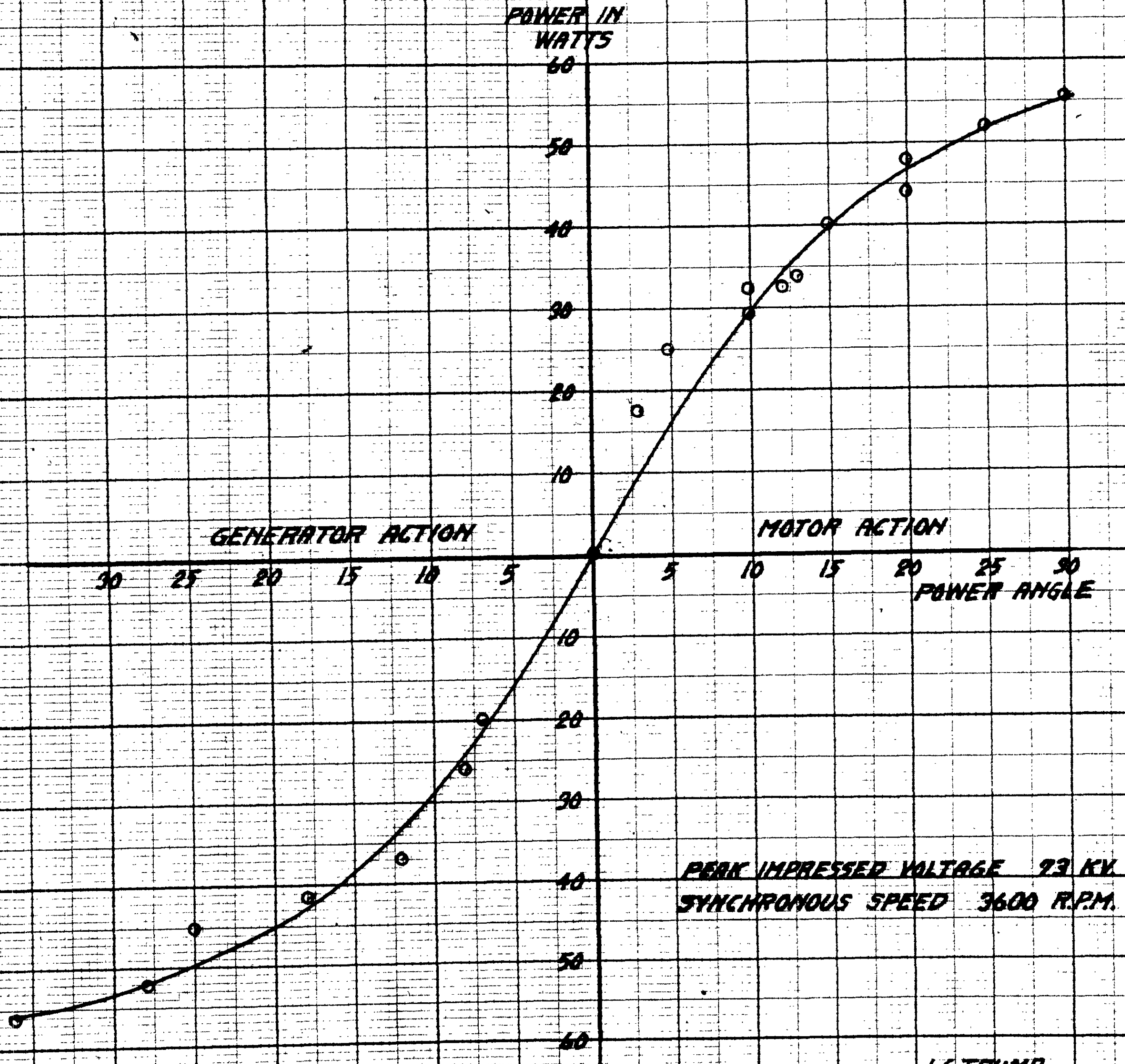


3 - 200W. 110-22000 POTENTIAL
TRANSFORMERS LOANED TO
M.I.T. BY SIMPLEX WIRE AND
CABLE CO., CAMBRIDGE, MASS.

FIGURE 32.

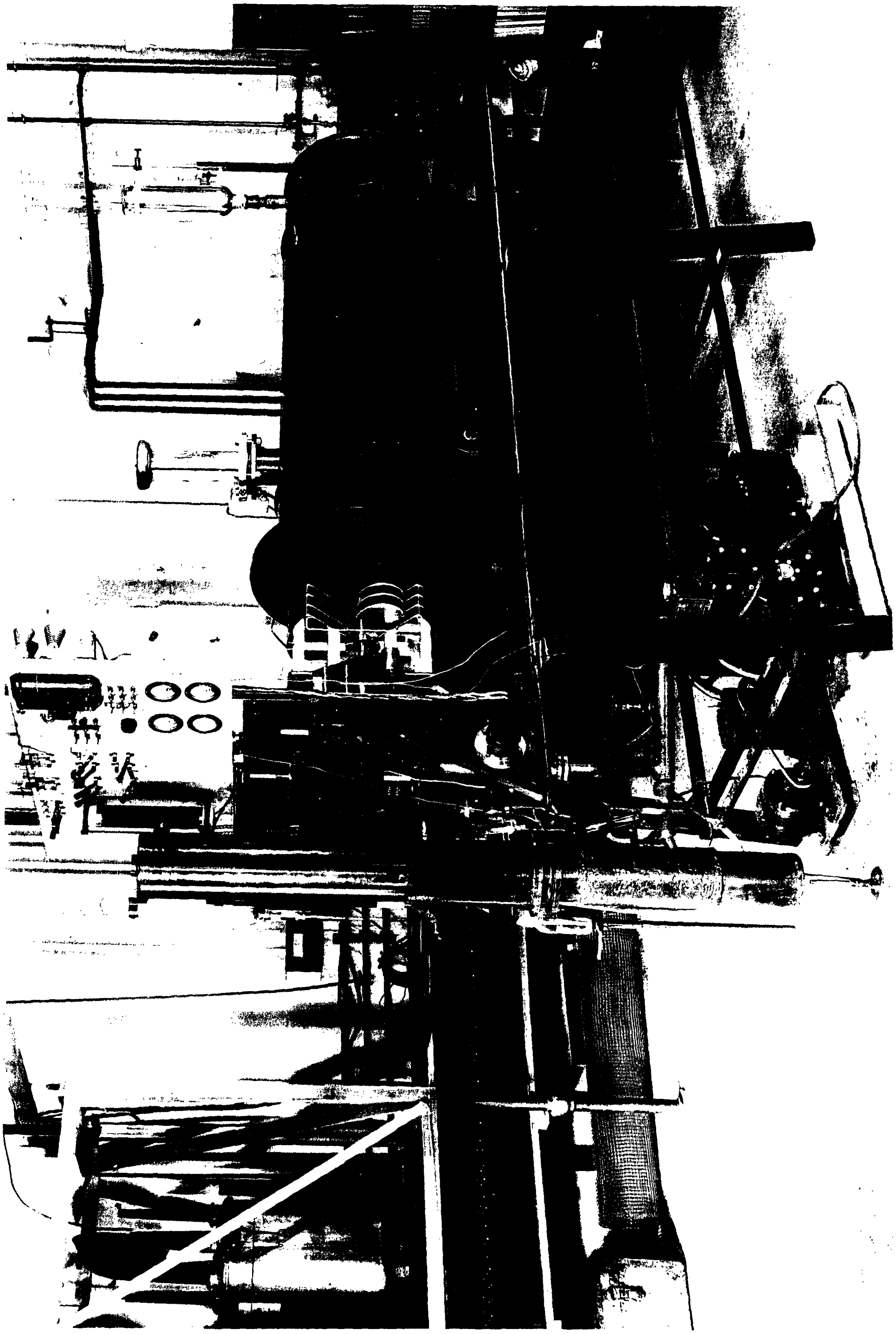
VACUUM ELECTROSTATIC SYNCHRONOUS MACHINE

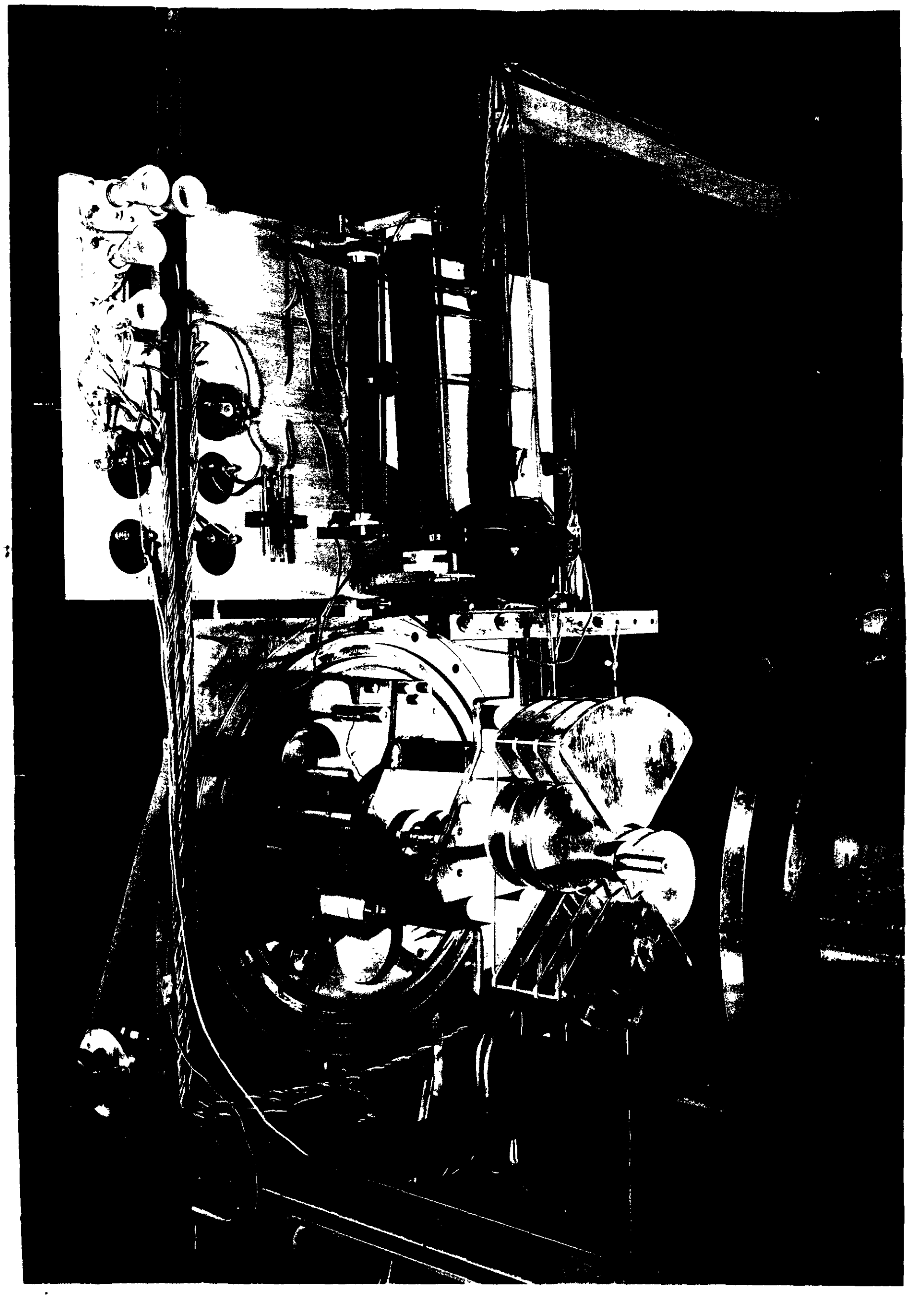
VARIATION OF DEVELOPED POWER WITH POWER ANGLE.



PEAK IMPRESSED VOLTAGE 73 KV.
SYNCHRONOUS SPEED 3600 R.P.M.

J.G. TRUMP
M.I.T. 1933.





CHAPTER V

ENGINEERING VACUUM TECHNIQUE

The production and maintanance of vacuums of the order of 10^{-6} mm. of mercury in large metal tanks has been accomplished only during the last few years. Since the development of the Gaede diffusion pump in 1915 small-volumed glass systems have been evacuated to pressures as low as 10^{-8} mm. It was well understood, however, that such low pressures could be attained and maintained only with great difficulty, that the system must be small and well outgassed, that it was fragile, quite unreliable, and that it was hampered by an extreme lack of flexibility in the manipulation of the internal apparatus. High-vacuum systems in the past have been characterized by the fragility and consequent unreliability of their physical structure, by their small volumes and lack of easy control, and by the general difficulty of evacuation and maintenance.

It was further generally believed that high vacua could not be practicably produced in metal tanks because of the tremendous amount of adsorbed and absorbed gases in metals, that the fabrication of vacuum-tight metal chambers offered special difficulties, and that the ruggedness of metallic construction offered no advantages in flexibility of control and adjustment of internal apparatus or in the transmission of mechanical power through the wall of the chamber, and had the further difficulty of opaqueness.

The first relatively-large-volumed metallic vacuum tank which disproved all of these objections and which pointed the way to a new era in vacuum technique was constructed by Van de Graaff at Princeton in 1931. The tank was 18 inches in diameter and 5 ft. long, of brass, and mounted on a trestle arrangement so that it could be rolled away from or against a brass end-plate which sealed its open end. The vacuum-tight joint between end-plate and the flange of the cylinder was made by pressing against two concentric rubber rings, the space between which was evacuated to form a guard ring.

A mercury diffusion pump of conventional design having a pumping speed at the tank of 55 liters per second and backed by an oil pump was used for evacuation. A liquid-air trap in the tank itself was used to remove the condensable vapors. This metallic vacuum system was completed in the fall of 1931 and a measured pressure of 5×10^{-7} mm. obtained. The tank was later brought to M.I.T. where it was further improved and developed and used for the research described herein.

In itsfinal form* this tank had eight 5/16" shafts passing into it for purposes of control and adjustment of apparatus within the tank, one 3/8" shaft for the transmission of mechanical power through the tank wall at 2,000 r.p.m., about twelve low-voltage electrical and electrometer leads, one 200,000-volt bushing, two windows for observation, one re-entrant liquid-air trap, a vacuum-tight valve between the tank and the pumping portion of the system so that the pumping system could remain in operation while the tank was open to atmosphere, an ionization gauge and a fore-vacuum thermocouple gauge in each of these two portions of the system, and an arrangement

---

* August, 1933.

whereby the tank could be rolled away from its end-plate to expose the internal apparatus. On a regular experimental schedule this tank has been rolled up tight against its face plate and pumped down to a pressure of 3 x 10^{-5} mm. in less than three-quarters of an hour. Pictures of the improved tank are given in Figs. 33 and 34.

An important innovation in vacuum technique suggested by Van de Graaff is the use of a positive-pressure grease-graphite seal to render vacuum-tight a shaft passing through the wall of the vacuum chamber for the purposes of control and the transmission of power. For small shafts for rotation by hand the simple arrangement shown in Fig. 35 suffices as a vacuum-tight seal. Fig. 37 shows the essential elements of an experimental shaft which was continuously rotated at 2000 r.p.m. without any evidence of leakage at a pressure of 5 x 10^{-5} mm., as recorded by an ionization gauge in the tank. The sealing medium is one of low vapor pressure and chosen for its inability to transmit shear. This medium fills a region between the wall of the tank and the shaft and is maintained (by means of a weighted plunger, for example) at a pressure greater than that urging the air to leak in toward the vacuum. This positive-pressure feature and the intimate and homogeneous nature of the barrier make leakage theoretically impossible; experimentally - within the limits of the detection apparatus - this conclusion has been varified. The sealing medium may be of grease or oil, for example. A mixture of grease and graphite was used in the small experimental seals, the grease serving as the sealing medium and the graphite preventing the grease from flowing. For the revolving shaft illustrated in Fig. 37 two opposing screw threads were turned on the shaft, which, for a particular direction of rotation, had the effect of scouring such grease as attempted to creep along the shaft back to the region of the seal. This method was found effective, since no grease-graphite appeared either at the atmospheric or the vacuum end of the seal after several hours of rotation.

This method of sealing power shafts into a vacuum tank is capable of handling the amounts of power associated with the large electric-power machines contemplated in this research. It is characterized by its extreme simplicity and effectiveness and the high efficiency of the transmission. For large shafts and high speed the use of oil is recommended, the oil being circulated in a closed system under pressure by methods illustrated in Fig. 37. The use of several seals in cascade, the use of a fore-vacuum ring at the atmospheric end of the shaft to remove the bulk of the pressure difference, and various other similar devices may be desirable to increase the reliability of large-shaft seals. It is believed that the experimental work on vacuum-tight shaft seals performed during this research has fully established the practicality of this method for meeting the problem of transmitting the large amounts of mechanical power in the proposed vacuum electrostatic power machines.

One of the greatest obstacles in previous high-vacuum technique has been the difficulty of locating leaks. The microscopic size of fault sufficient to ruin the high-vacuum possibilities of a system is well known; in the past, the location of leaks in a vacuum system of any complexity has often held up research for days, weeks, months, and even years. Any technique which will enable the certain and rapid location and correction of faults in a high-vacuum system is of prime importance. It has been a specific aim in this research to develop such methods and thereby establish high-vacuum technique on a sound, reliable engineering basis.

It is recognized that the main source of leaks in a metallic system will be at the various joints and connections rather than in the unbroken surface of the vacuum enclosure. Accordingly the policy of enclosing all such joints with guarding chambers which can be quickly evacuated to fore-vacuum pressure by means of a small oil pump, has been generally followed. The suspicion of a leak in any joint so provided with a guard ring can be verified by evacuating the guard ring with a fore-pump. This would have the effect of reducing the rate of any leakage by a factor of at least one thousand, and the consequent improvement or lack of improvement in the vacuum condition within the chamber, as indicated by an ionization gauge, would establish almost at once the correctness of the suspicion. In the experimental tank mentioned above, guard rings have been used around electrical leads into the tank, around all removable connections such as the joint between metallic pump case and metallic condensation trap, housing between condensation trap housing and metallic end-plate, between end-plate and flange of vacuum tank cylinder, between the rings of vacuum-tight valve seats, and between glass to metal flanges. Means were also provided for quickly establishing a fore-vacuum over vacuum shaft seals, over windows in tank wall, and over unbroken areas of the tank surface. By painting the metallic surface of the tank with a heavy internal coat of insulating paint such as Glyptol, not only were any small leaks closed up, but it also became possible to test the general metallic surface for leaks with a standard induction leak tester. The entire system could be systematically checked for leaks with high probability of success within an hour. While the new metallic vacuum systems now contemplated will embody these features in still higher degree, the experimental vacuum system which was used in this research is believed to have attained a degree of reliability and flexibility never approached by any other system, and has shown the way to ~~and~~ the practicability of sound engineering vacuum technique.

The experimental work on metallic vacuum systems has indicated that vacuums between 10^{-6} mm. and 10^{-7} mm. of mercury can be obtained in large systems with proportionate pumping speeds when the metallic surfaces are clean and bright though unoutgassed. Certain metals such as stainless steel and nickel are expected to show advantages over others for such systems since it is evident that, with the eliminating of organic materials, the limitation in degree of vacuum is caused by the rate of gas given off by the metal parts.

It is well known that metals can be outgassed by heating in vacuum, by positive-ion bombardment, and by serving as the electrodes in an electric discharge. These methods are expected to lead to further improvement in the degree of vacuum which can be set up in a metal system.

A method of outgassing by heating, which shows great possibilities, will be now described. The vacuum tank contains within and insulated from it a second thin-walled shell of stainless steel or nickel, etc. This shell is itself vacuum-tight and is evacuated by a separate pumping system. The region between the liner and the tank is evacuated to a pressure of about 10^{-6} mm. by the usual means. In practice the whole system is first pumped down together. An electric current is then passed through the liner which heats it to as high a temperature as feasible. This results in the rapid outgassing of the metal liner and all it contains, the products being carried off by the pumping system. By this means the adsorbed and absorbed gases in the internal tank system can be rapidly removed and an equilibrium pressure established which is much lower than that between this liner and the unoutgassed main tank itself. This method has the advantage of simplicity and effectiveness and should lower the pressure ratios by at least a factor of ten.

The limit to which the pressures can be reduced by this means is fixed by the amount of metal surface looking into the inner vacuum system which cannot be outgassed. It is evident that the pump and trap surfaces which are part of the inner vacuum shell are necessarily in equilibrium with the gases being pumped. Accordingly, the pressure in the inner system is that equilibrium pressure maintained largely by the unoutgassed pump system surfaces. No system, whether glass or metal, has ever been produced in which every area of the enclosure was fully outgassed.

The use of a metallic molecular pump* of novel design in place of a diffusion pump to evacuate the inner vacuum shell removes this limitation. Such a pump requires no trap and may itself be operated at high temperature so that the entire area looking into the inner high-vacuum shell can be thoroughly outgassed. This arrangement is illustrated in Fig. 38. With the development of such pumps it can be shown by calculations based on the known rate of gas emission of out-

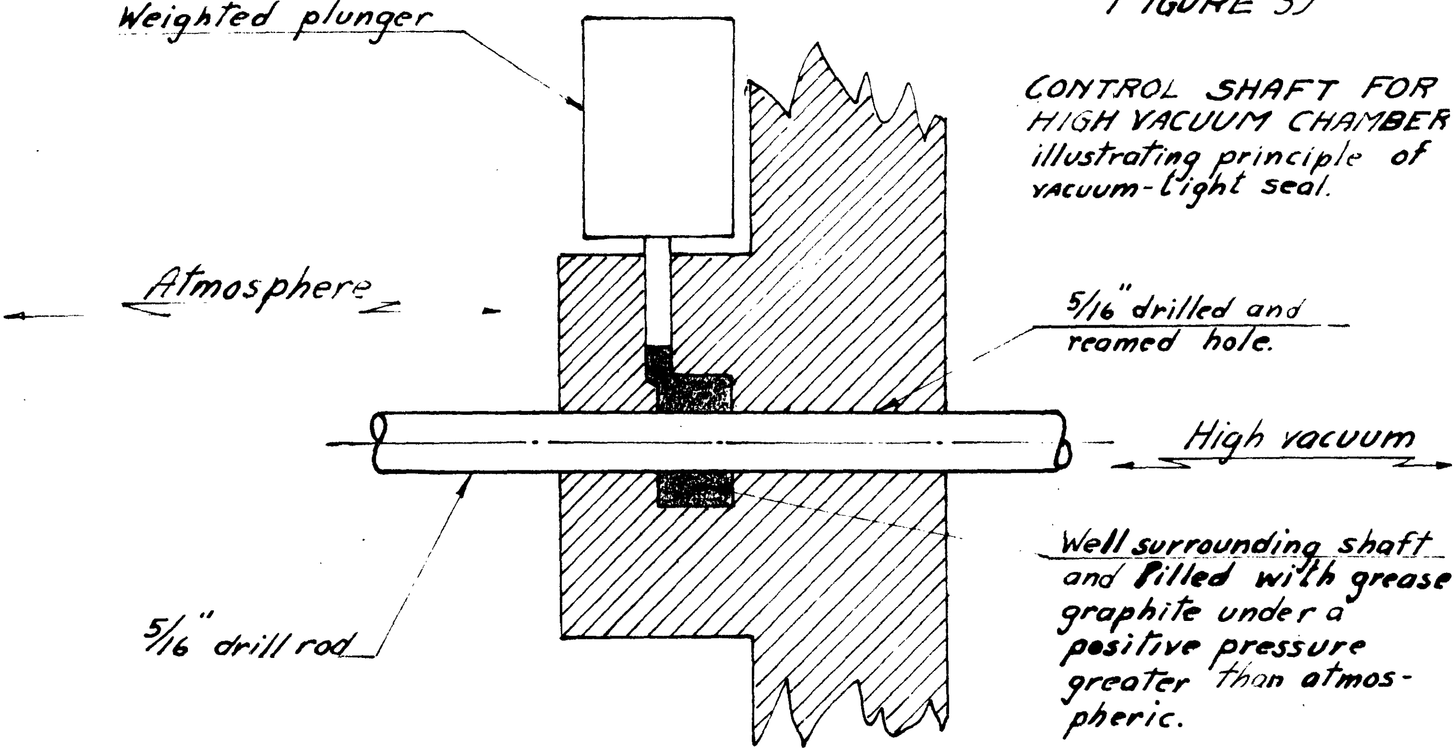
---

* Suggested by R. J. Van de Graaff.

gassed metals, the pumping speed, and the tank volume, that pressures as low as or lower than 10^{-9} mm. Hg. can be maintained in large metal tanks.

FIGURE 35

CONTROL SHAFT FOR HIGH VACUUM CHAMBER illustrating principle of vacuum-tight seal.



VACUUM-TIGHT BEARING SEAL FOR LARGE POWER SHAFTS.

Figure 36

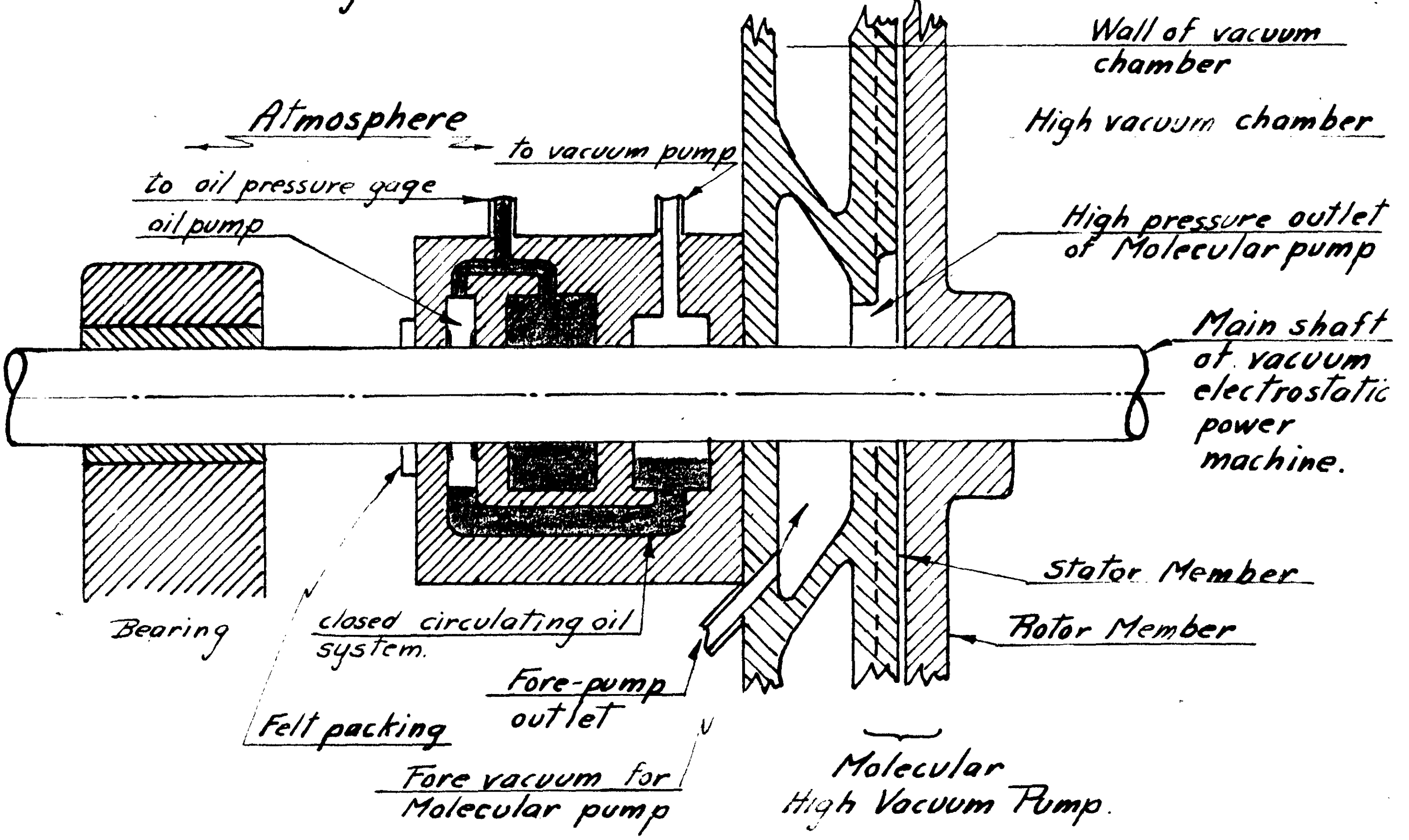
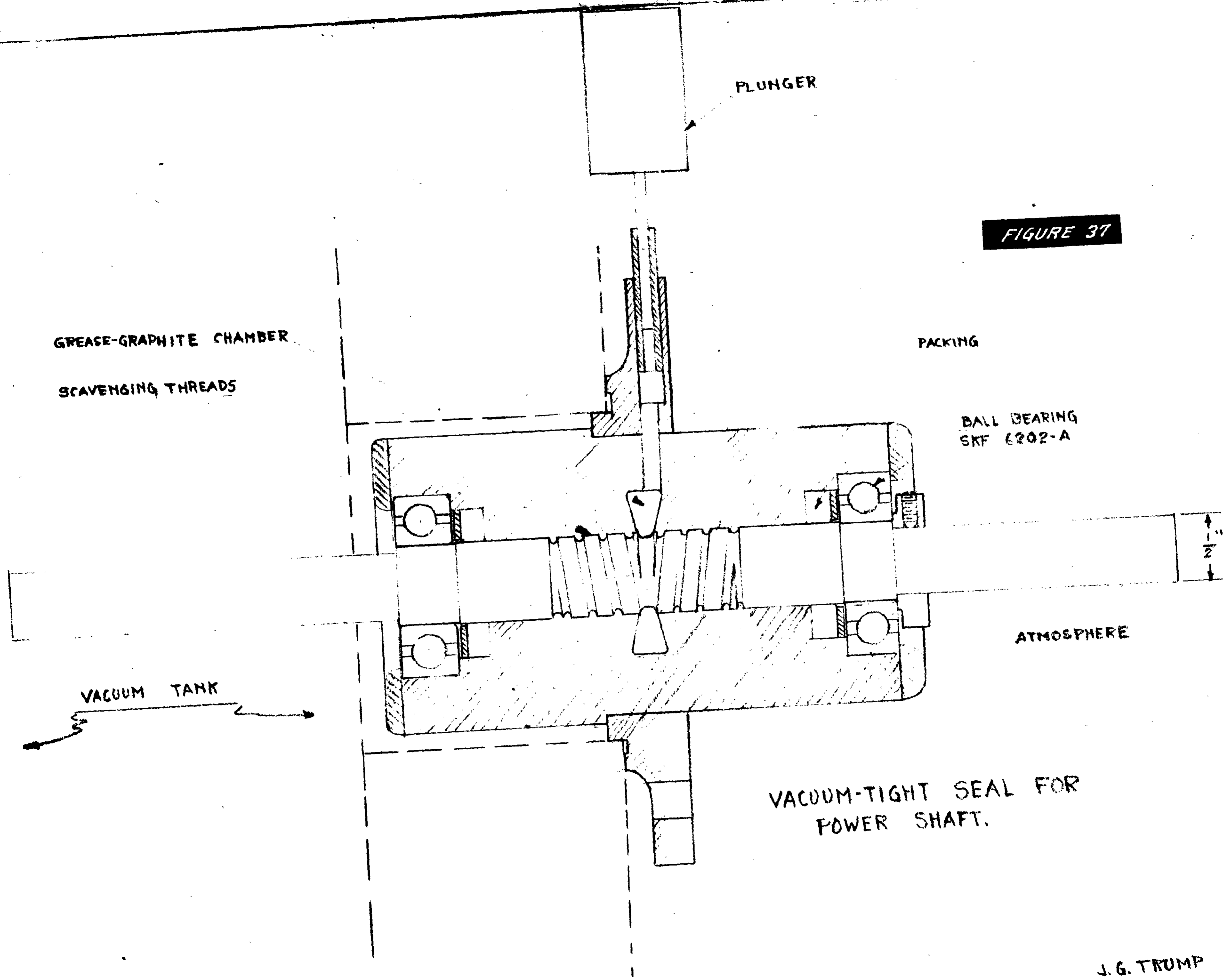


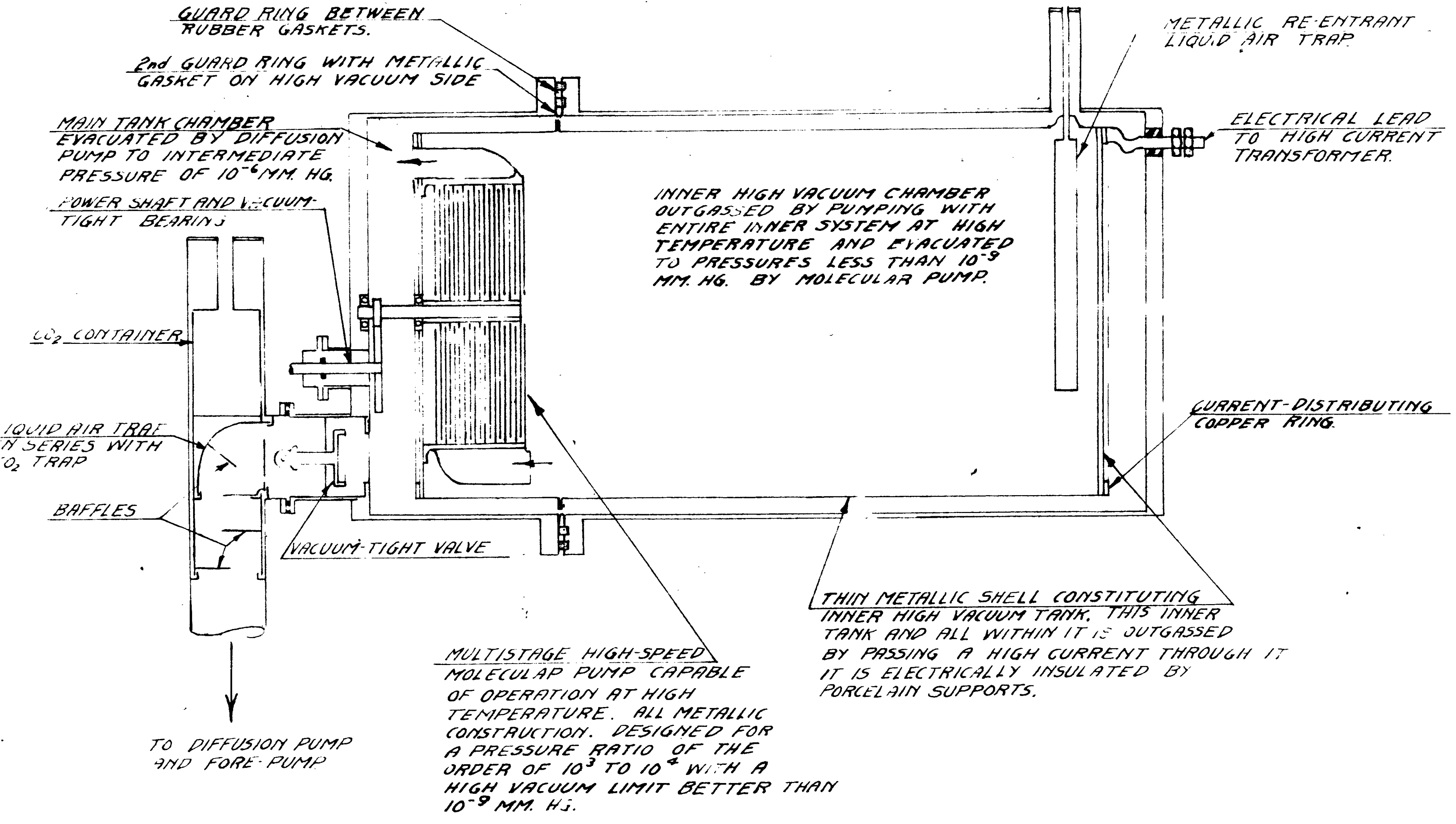
FIGURE 37



VACUUM-TIGHT SEAL FOR
POWER SHAFT.

J. G. TRUMP
M.I.T. 10-26-33.

FIGURE 38
OUTGASSABLE METALLIC HIGH VACUUM TANK
AND MULTISTAGE MOLECULAR PUMP



J.G.TRUMP
MIT 11-6-33

CHAPTER VI

VACUUM AND MATERIAL INSULATION

The technical and economic practicability of the application of vacuum electrostatics to the electric-power field depends in large degree on the practical realization of the unusual insulating qualities of high vacuum. What experimental information is available on vacuum insulation for high voltages has in general appeared as secondary results of experiments directed primarily toward other ends. It is only very recently that an intensive, scientific investigation of this field has been inaugurated.[1]

Some experimental work[2] in vacuum at low voltages (below 30,000) has demonstrated that cathode gradients as high as 5.5×10^6 volts per centimeter can be supported at the cathode electrode.[3] It is well established that anode gradients many times this value can be readily maintained. Recent experimental work on high-voltage X-ray tubes has indicated that voltages as high as 650,000 volts can be reliably maintained with a cathode gradient of about 100,000 volts per centimeter.[4] While this information confirms the belief in the efficacy of vacuum insulation for high voltages and high gradients, it cannot be

---

[1] A doctor's research tending to establish definitely the factors and limitations of high-voltage vacuum insulation is now being carried on by Mr. H. W. Anderson at the Massachusetts Institute of Technology.

[2] See Chapter I.

[3] A test of unoutgassed highly-polished steel electrodes indicated that a voltage of about 200,000 with a cathode gradient of 750,000 could be insulated in a vacuum of about 5×10^{-6} mm. Hg. This test was not carried to higher voltages.

[4] Crane and Lauritsen, Review of Scientific Instruments, Vol. 4, No. 3, p. 118, March, 1933.

construed in any sense to define its practical voltage and gradient insulating limitations. On the contrary, in view of the lack of controlled conditions, the imperfections of the vacuum, the random choice of electrode material for anode and cathode, and (what is highly important) the inadequate attention to the surface treatment of the electrodes, (some or all of these difficulties characterized all of the previous high-voltage-vacuum insulation experiments) it can be most assuredly stated that the real insulating possibilities of high vacuum are still to be established.

A mechanism of breakdown in high vacuum suggested by L. C. Van Atta, R. J. Van de Graaff, and H. A. Barton[1] accounts for the onset and maintenance of discharge between electrodes in vacuum as due to ionization at the electrode surfaces caused by impacts of ions, electrons, and photons. This theory supposes that an electron impinging on the anode produces, on the average A positive ions and B photons which reach the cathode, and that a positive ion impinging on the cathode liberates C electrons, and a photon liberates D electrons which reach the anode. The condition for a discharge is given by

$$AC + BD > 1.$$

It is quite evident that the cathode coefficients C and D depend on the work function and surface condition of the cathode electrode, and that proper choice of cathode material, and polishing, outgassing, or otherwise altering the superimposed surface condition produced by adsorbed gases, projections, and other surface debris, will reduce to a very considerable extent their value. Similarly, the anode material and surface treatment will affect very considerably the anode coefficient A and B. The use of insulating films on the cathode surface[1] and of positive grids over the anode surface, as well as other similar artifices, will have a pronounced effect on the breakdown coefficient and will warrant careful investigation. It is unlikely that the anode and cathode coefficients will, in general, be affected in exactly the same way; and particularly, it is highly improbable that the best combination of electrode material and treatment could be obtained by a fortuitous choice without a careful, controlled, quantitative, scientific study. It is believed that such an investigation may, as an end result, lead to the reliable insulation in vacuum of voltages of one or more millions of volts at cathode gradients of the order of several millions of volts per centimeter. Such vacuum insulation properties, applied to the power field as herein disclosed, would produce power machines much more compact and economical than the most modern electromagnetic machines, besides introducing features of high voltage and efficiency which are now unattainable.

Material Insulator for Use in High Vacuum

The development of material insulators for use in high vacuum as high-voltage electrode supports, vacuum-tight diaphragms, etc. and characterized by high voltage and gradient breakdown strength is a second insulating problem of major importance. The problem of securing the necessary compactness in an insulator is complicated by the necessity for good mechanical characteristics and by the limited choice of insulating material which, from an outgassing point of view, is suitable for

---

[1] Physical Review, 43, p. 158, February, 1933.

use in vacuum.

The problem of volume breakdown through the insulator offers no particular difficulty. Van de Graaff has suggested the use of many thin laminae of insulating material, such as pyrex, quartz, porcelain, etc., each coated on one side with a thin conducting film, the arrangement then stacked up and fused together to form a solid insulator with a controlled gradient. The volume breakdown strength per unit length would then be closely the sum of the strength of each lamina therein. Since 0.025 cm. of pyrex will withstand a voltage of 80,000, a built-up insulator made of such laminae would have a volume breakdown of over three million volts per centimeter.

The chief limitation in material insulators for use in vacuum is due to surface leakage and breakdown. A method of overcoming this surface breakdown limitation is illustrated in Fig. 39. The highly-corrugated surface results in a surface leakage path many times the length of the insulator.

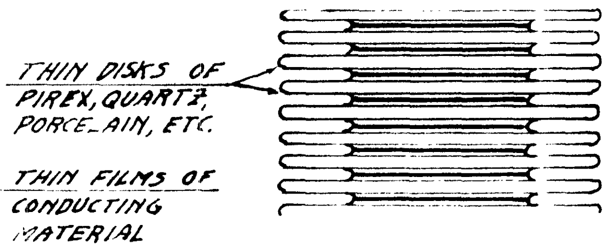
In a recent test made during this investigation of one element of a corrugated Isolantite insulator a voltage of 130,000 was withstood by an axial insulator length of 0.68 cm. with a leakage less than 0.2 m.a. The length of the insulator leakage path (following along the surface of the corrugation) was 2 cm. The same section of insulator sparked-over at 16,000 volts in air. This test, together with the further ideas presented below definitely establishes the practicability of matérial insulators of remarkable compactness for use in vacuum.

The insulator is, however, still externally exposed to the high-voltage parts and therefore liable to electron or positive-ion bombardment which may precipitate breakdown, or to localization of electric stress which may result in an emission from its surface with similar effect. These difficulties may be overcome by providing over each corrugation a well-outgassed metal ring so arranged (see Fig. 40) that the insulator, as viewed from the exterior, is a well-outgassed metal unit. The insulating material is thereby shielded from high-speed ion bombardment and, more important, the high-voltage insulator problem has been reduced to a low-voltage insulator problem. This is evident, since any length of insulator leakage path is subjected only to the voltage difference between the two outgassed metallic rings, and has no way of determining the potential at which these two rings exist. This method indicates, then, how a high-voltage insulator may be built up of separate low-voltage elements, each element (regardless of its position) retaining in a complete sense, its electrical individuality. Thus an insulator as in Fig. 40, composed of 20 sections each withstanding only 50,000 volts, would have a total insulator voltage strength of 1,000,000 volts. Furthermore, each section may again be subdivided, as in Fig. 41, so that the 50,000 volts is again broken up with subsequent decrease in the cumulative electric-stress demands upon the insulating material.

It is suggested that such an insulator be built up of stacks of disk-shaped porcelain, a thin conducting film (of Roman gold or other material) painted on the surface to form the conducting areas, and the assembly fired and fused into a unit. Since the loading of such an insulator can by proper design be made purely compressive, it is evident that good mechanical characteristics for this sort of loading can be obtained. It is also possible that such an insulator could be made of a solid core of material such as textalite, treated against outgassing by coating with or baking on a vacuum-tight substance, and over which are stacked annular rings performing the function and provided with the metallic edges and divisions as the corrugations mentioned above.

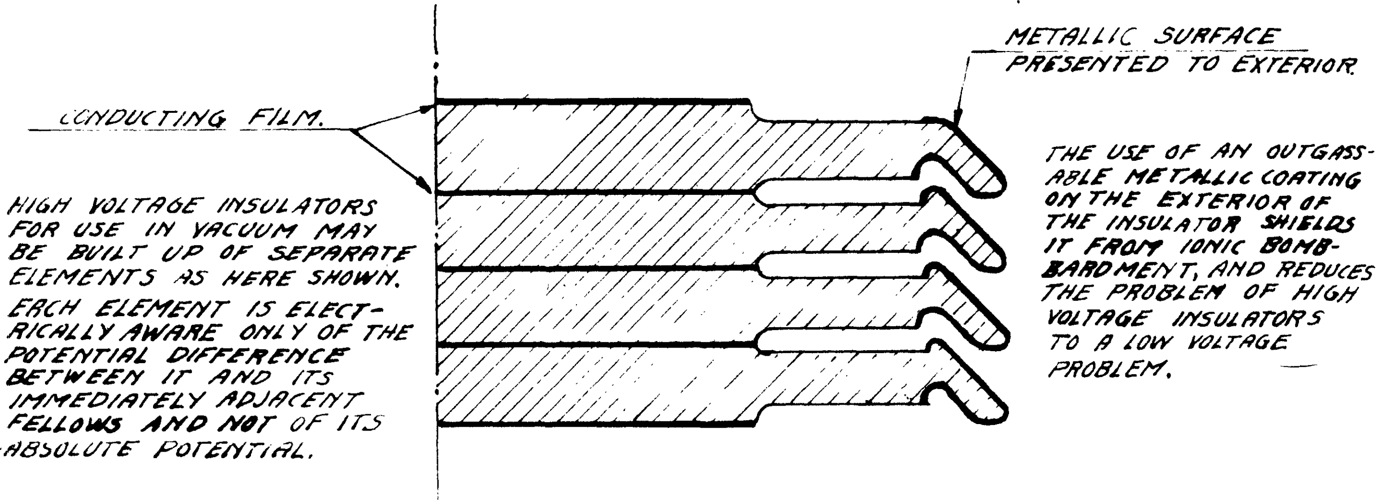
It is clear, since the above description has indicated how a high-voltage insulator for vacuum can be designed so as to involve essentially only a low-voltage insulation problem, solutions for which are already understood, that not only can material insulation be built for a million volts or more in vacuum, but they can quite certainly be designed with a concentration of insulating strength many times greater than any material insulator now known. It is further evident that the units of a built-up insulator of this type can be studied separately and intensively, and that the performance of the assembly can then be accurately predicted on the basis of the unit study. A thorough investigation of the surface characteristics of insulating materials, combined with a study of the ideas and methods discussed above, is essential to theattainment of compact material insulators to supplement vacuum in the insulation of vacuum electrostatic power apparatus.

FIGURE 39



SIMPLE INSULATOR FOR USE IN VACUUM SHOWING METHOD OF SECURING HIGH VOLUME BREAKDOWN STRENGTH BY THE USE OF THIN INSULATING LAMINA SEPARATED BY CONDUCTING LAYERS.

FIGURE 40

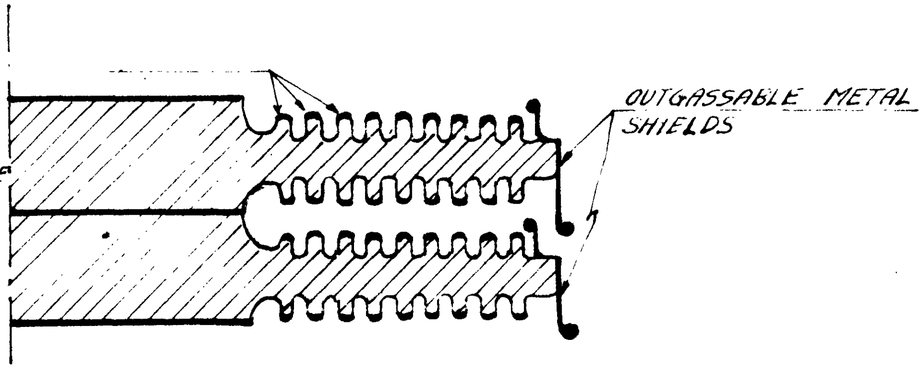


HIGH VOLTAGE INSULATORS FOR USE IN VACUUM MAY BE BUILT UP OF SEPARATE ELEMENTS AS HERE SHOWN.

EACH ELEMENT IS ELECTRICALLY AWARE ONLY OF THE POTENTIAL DIFFERENCE BETWEEN IT AND ITS IMMEDIATELY ADJACENT FELLOWS AND NOT OF ITS ABSOLUTE POTENTIAL.

THE USE OF AN OUTGASSABLE METALLIC COATING ON THE EXTERIOR OF THE INSULATOR SHIELDS IT FROM IONIC BOMBARDMENT, AND REDUCES THE PROBLEM OF HIGH VOLTAGE INSULATORS TO A LOW VOLTAGE PROBLEM.

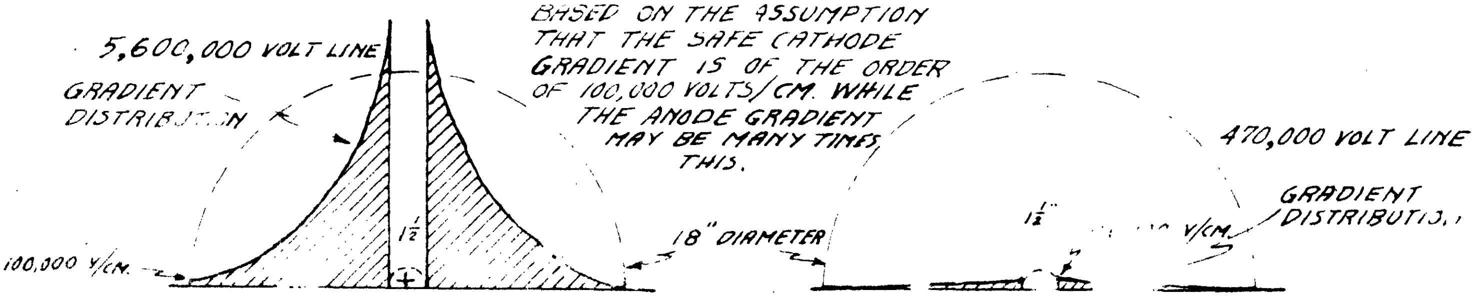
FIGURE 41.



THE TIPS OF THE ANNULAR CORRUGATIONS ARE METAL COVERED. THIS BREAKS UP STILL FURTHER THE LOW VOLTAGE INSULATION PROBLEM BETWEEN ELEMENTS.

FIGURE 42

EFFECT OF POLARITY OF CENTRAL CONDUCTOR ON THE INSULATION STRENGTH OF VACUUM TRANSMISSION LINE.



BASED ON THE ASSUMPTION THAT THE SAFE CATHODE GRADIENT IS OF THE ORDER OF 100,000 VOLTS/CM. WHILE THE ANODE GRADIENT MAY BE MANY TIMES THIS.

CHAPTER VII

VACUUM TRANSMISSION LINE

The unique insulating properties of high vacuum which makes possible for the first time the generation of high-voltage, direct-current power in large blocks, also makes possible the efficient and economical transmission of this power over long distances. The essential features of such a vacuum-insulated transmission line* are discussed in detail below.

The high-voltage vacuum-insulated transmission line consists essentially of a positive conductor running axially along a highly-evacuated metallic tube constituting the return conductor. It is an important feature of this proposed transmission line that the central conductor be positive, since this geometrical arrangement, as has been pointed out, takes advantage of the high-voltage gradients which can be supported at the anode surface and results in a much reduced gradient stress at the cathode surface. Assuming that the maximum gradient which can be supported at the cathode is 100,000 volts per centimeter, while the anode gradient may be of the order of tens of millions, Fig. 42 illustrates the maximum voltages which can be safely insulated by a vacuum transmission line of given dimensions when the central conductor is positive and when it is negative.

The proposed vacuum transmission line would be capable of transmitting direct-current power at voltages of the order of a million or more, in substantially unlimited amounts, over distances many times

---

* First suggested by R. J. Van de Graaff.

greater than even the longest of modern alternating-current power systems, and with a relative energy loss many times less. It is estimated, as will be described below, that the initial investment and operating cost of a high-power vacuum transmission line are less than for modern power transmission lines, and that it is inherently capable of far greater reliability.

A proposed construction for a 1,000,000-volt, 500,000-kw. transmission line is illustrated in Fig. 43. The total energy loss per hundred miles in a double-circuit line of this rating and construction is estimated at about 0.2 per cent.

The concentric high-vacuum, fore-vacuum, and protective-seal construction shown in Fig. 43 is suggested for maximum reliability, simplicity, and economy. The fore-vacuum and high-vacuum tubes are made integral by means of supporting webs, thus forming an exceedingly strong and light unit capable of resisting the atmospheric pressure as well as other mechanical loads. The fore-vacuum serves the dual purpose of reducing (by a factor of about one million) the effect of any faults in the inner high-vacuum shell, and of providing a fore-vacuum line of high conductivity to serve as the backing for the relatively-closely-spaced high-vacuum diffusion pumps. This makes possible the location of mechanical fore-pumps at intervals along the transmission line from 5 to 20 miles apart. The vacuum-tight outer seal eliminates the effects of any but extremely large faults in the fore-vacuum shell. This seal could be a grease-graphite layer maintained at a positive pressure greater than atmospheric, or a layer of some other homogeneous and viscous substance, or conceivably a layer of very gummy rubber. The high vacuum of the transmission line is thus protected by the vacuum-tight inner metallic shell, which in turn is protected by the fore-vacuum which is confined in a second metallic vacuum-tight shell, which in turn is protected by a positive-pressure, vacuum-tight seal. It is believed that this construction is capable of a high degree of reliability.

The method of supporting the central high-voltage positive conductor is illustrated in Fig. 44. The insulators are of the controlled-gradient type described in Chapter VI and are mounted in groups of three, set in a transverse plane at 120 degrees relative to each other. Any force tending to move the central conductor from its position to symmetry can result only in a purely compressive strain in the insulators. The central conductor is allowed axial movement by the loose construction of the metal collar in which the pin insulators terminate. The separation between points of support of the central conductor will vary from 10 to 20 ft., depending on the mechanical strength of the conductor, the diameter of the high-vacuum shell, and the operating voltage. The design must be such that the rate of development of mechanical forces tending to resist displacement of the central conductor from its position of symmetry, is greater than the rate of development of unbalanced electrostatic forces tending to increase such displacement. This consideration will generally result in a central conductor of cross-sectional area several times that required to conduct efficiently the rated current of the line, and hence results in a line which in this respect has an extremely large overload current and power capacity.

The method of isolating sections of the vacuum transmission line, from a vacuum point of view, is illustrated in Fig. 45. The vacuum-tight insulating diaphragm is designed to withstand full atmospheric pressure on either side and is again of the controlled-gradient type. The two adjacent sections of the high-vacuum line are connected by a by-pass which can be opened or closed by a manually- or automatically-operated valve. The two adjacent sections of the fore-vacuum line are separated by a vacuum-tight metallic web and again connected by a valve-controlled by-pass. This division of the vacuum transmission line into sections which can be readily isolated greatly limits the spread of difficulties due to vacuum faults, and facilitates the repair of the faulty part. The sectionalizing of the vacuum system is thus recommended for increased reliability.

The evacuated condition of the transmission line is maintained by a system of high-vacuum diffusion pumps and fore-vacuum mechanical pumps. In a well-outgassed system the diffusion pumps may be as much as 500 to 1000 ft. apart. A section of the transmission line showing the high-vacuum diffusion pumps is shown in Fig. 46. Two pumps are connected in series for high reliability, the second being backed by connection to the fore-vacuum line. These pumps are characterized by their simplicity, reliability, and low cost of operation. They utilize a low-vapor-pressure oil as the pumping medium and are air-cooled. The design of the heater element results in a new economy of operation; in a pump of this type tested at Princeton a pumping speed of 50 liters per second was realized with a power expenditure of about 50 watts. The series arrangement of pumps is used to prevent free access of the fore- to the high-vacuum lines should one pump fail. It also results in a higher pumping speed and an increased pumping-pressure ratio under normal conditions. A manually- or automatically-operated cut-off valve is provided between the diffusion pumps and the high-vacuum line. An automatically-recording high-vacuum gauge is provided at each diffusion-pump installation.

The pumping speed of the annular-ringed-section fore-vacuum line is made such that the mechanical pumps required to maintain the necessary evacuated condition therein may be located ~~at~~ as much as 20 miles apart. With a well-outgassed fore-vacuum system and a fore-vacuum pressure between 10^{-2} to 10^{-1} mm. Hg. this presents no special difficulties. Large fore-vacuum pumps of conventional design would be installed at these pumping stations.

It is estimated that the total power per hundred miles required to maintain the necessary evacuated condition within the transmission line of Fig. 43 would be about 0.1 per cent of the power rating of the line. Thus it is apparent that only a negligible amount of energy is required for meeting the pumping requirements of a vacuum-power transmission line.

FIGURE 43

SECTION OF A 1,000,000 V 500,000 KW D-C TRANSMISSION LINE

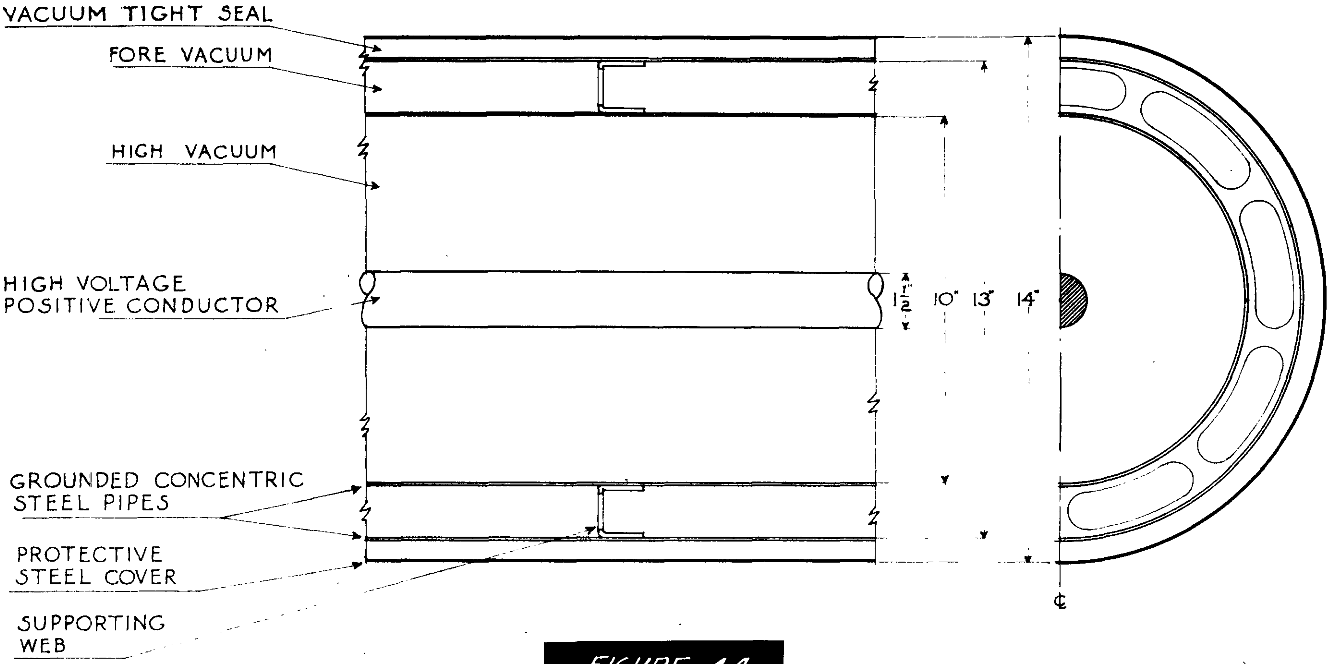
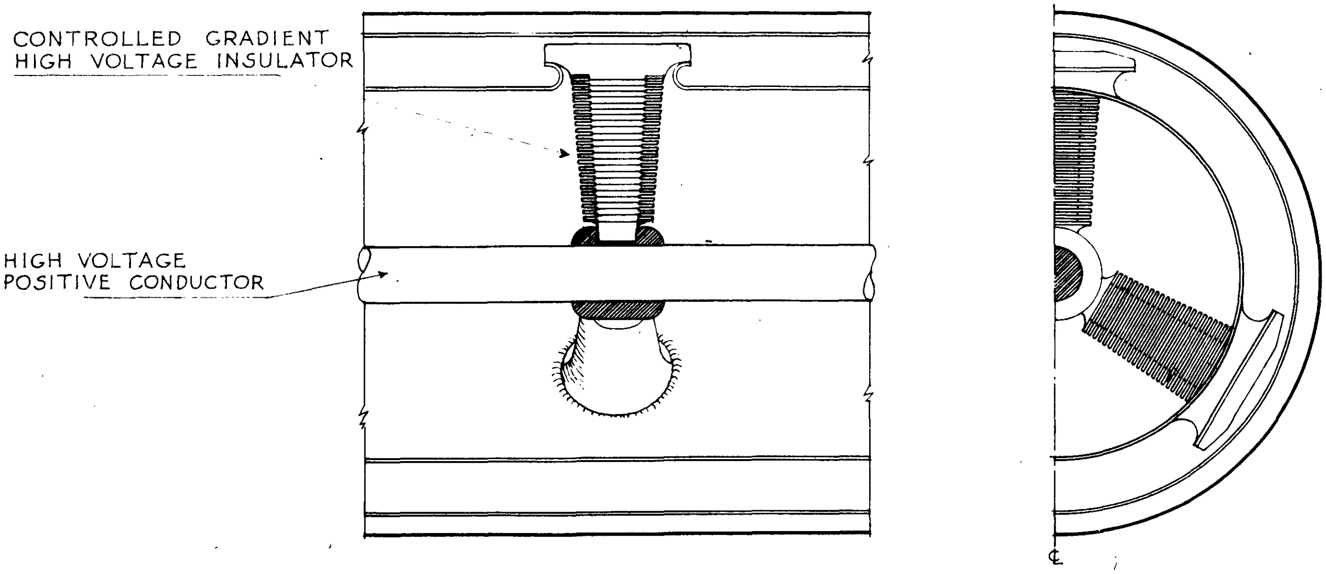


FIGURE 44

METHOD OF SUPPORTING HIGH VOLTAGE CONDUCTOR



J. G. TRUMP
MASS. INST. TECH
1933.

FIGURE 45

METHOD OF ISOLATING SECTIONS OF VACUUM TRANSMISSION LINE

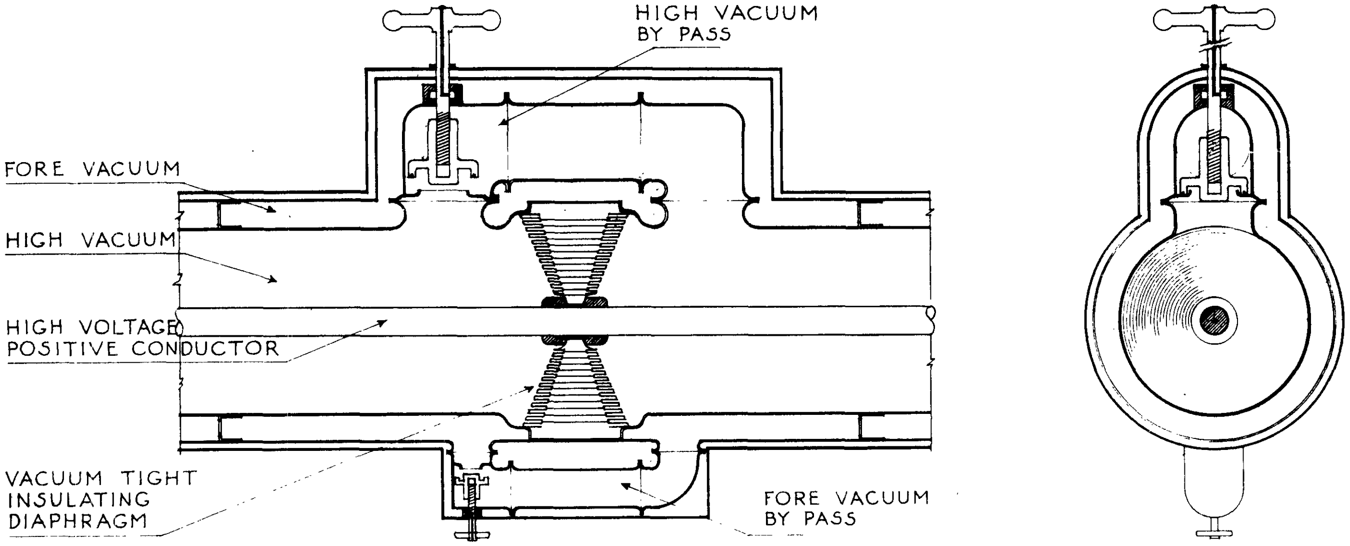
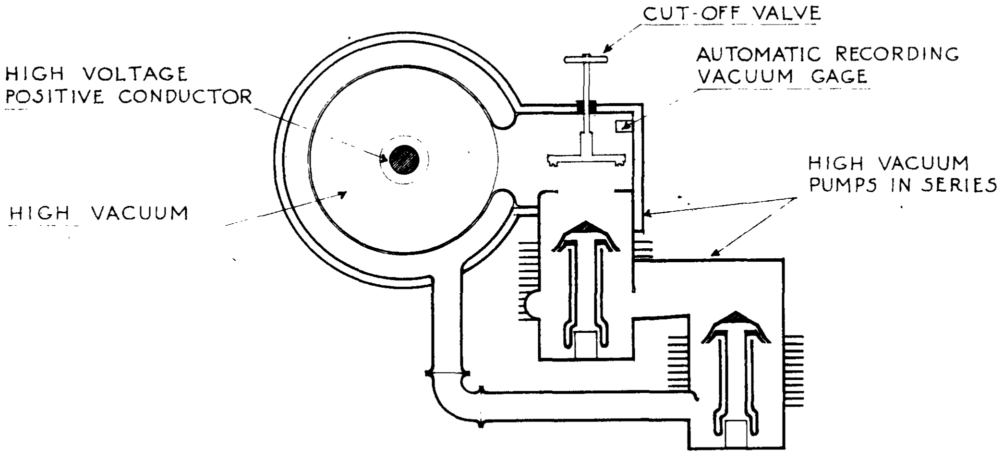


FIGURE 46

SECTION OF TRANSMISSION LINE SHOWING HIGH VACUUM PUMPS



J.G. TRUMP
MASS. INST. TECH.
1933.

CHAPTER VIII

ELECTRONIC SWITCHES

This chapter describes a new type of switch for use in high-voltage, direct-current power systems and capable of interrupting currents of the order of 1000 amperes and of withstanding back voltages of the order of 1,000,000 volts.

This switch performs its function by permitting or interrupting electron flow in vacuum between two terminals of the high-voltage line. It consists essentially of an electron-emitting surface, a control grid, an accelerating grid and a plate. A proposed arrangement of these elements is shown in Fig. 47.

The functions of these elements are as follows: During conduction the control grid is maintained slightly negative and serves to focus the electrons from the emitter in many thin streams directed toward the centers of the corresponding number of holes in the grid structure. The accelerating grid is maintained positive and serves to accelerate these electron streams toward the plate. The design is such that these electrons reach the plate with just sufficient energy to cause them to be absorbed, the net voltage between emitter and plate being preferably of the order of a few volts, though not limited to small voltages.

To open the circuit the control grid is made negative by an amount comparable with the accelerating voltage. This prevents electrons from passing beyond the control grid and hence reduces the emitter-to-plate current to zero. The accelerating voltage may, or may not, be allowed to remain on the accelerating grid. For long-period interruptions it would probably be desirable to reduce the accelerating grid potential to that of the emitter. When the switch is insulating, full line voltage minus the accelerating grid potential exists between the accelerating grid and plate. The spacing of these elements must be such that these voltages can be safely withstood in vacuum.

The practicability of the above arrangement is illustrated by the following analysis: The accelerating voltage required to overcome the space charge due to a current density of 0.125 ampere per square centimeter between accelerating grid and plate for a separation (calculated between thin parallel planes) of 5.86 cm. is 15,000 volts. This spacing is of the order of magnitude sufficient to adequately insulate 1,000,000 volts in high vacuum with sufficient margin to take care of the physical dimensions of the grid. This same accelerating voltage also overcomes the space-charge effects of this current density and of the control grid in the region between the emitter and the accelerating grid. In a proper design the plate current should be equal to the current passing beyond the control grid, since otherwise accelerating grid currents and losses would result. Various mechanisms for preserving this saturation feature for all values of current, by changing either the accelerating-grid or the control-grid voltage, can be devised.

In the above calculation, the plate potential relative to the grid potential was zero. By slightly increasing the accelerating-grid potential, or by reducing the spacing grid-to-plate, the electrons can be caused to reach the plate with sufficient energy to cause them to be absorbed. Low emitter-to-plate voltage means low losses. It is desirable that this voltage be small, however, not only to realize small plate losses, but also to prevent secondary emission from the plate by the impinging electrons. Such secondary emission could be greatly reduced, should this be necessary, by providing an additional grid closely adjacent to the plate and maintained at a small positive voltage relative to it.

The control grid is so designed as to focus the electrons from the emitter into many thin streams so directed that they will pass through the grid. By this focusing mechanism the accelerating-grid current can be greatly reduced under saturation conditions. The corresponding grid loss is therefore similarly reduced. This results in simplification of design, since the necessity of designing the grid to dissipate large grid losses in heat is reduced. A suggested focusing mechanism is shown in Fig. 48. The focusing action of the control grid could be designed in such a way that the electron streams focus in the plane of the accelerating grid. The divergence of the electron streams, which then follows in the interval from accelerating grid-to-plate, reduces the space-charge effect of the focusing. The fact that the electron velocity is greatest near the accelerating grid, where the streams are of greatest density, is also advantageous from the space-charge point of view. Nevertheless, considerable allowance must be made in the design for the heightened space-charge effect of many focused electron streams.

The control grid also serves the important function of stopping the flow of electrons when the switch is to be insulating. This may be done by spilling suddenly a large negative charge on this grid, thereby setting up a space-charge barrier sufficient to overcome the effect of the accelerating grid and plate potential. This switching action is capable of extreme rapidity, the time required depending only on the time constant of the control circuit. The close proximity of the control grid to the emitter enables this to be done with moderate negative control voltage. The line voltage itself is insulated between accelerating grid and plate. The relatively-low voltages required by the control grid simplifies the problem of automatic switch control. The condenser which spills the charge onto the control grid may be actuated by abnormal line conditions, using mechanisms (some of which have been devised) not difficult to work up for any specified situation.

The use of concentric cylindrical construction of the elements offers important advantages in the outbalancing of electrostatic forces and in the reduction of space-charge effects due to a given current density at the emitting surface. The control and accelerating grids and the plate also serve to reflect heat back to the emitter and thus to reduce emitter heat loss. It is understood that the end construction of these concentric cylinders would be such that the electrons must pass through the grids.

An effective cylindrical emitting surface, 1 ft. in diameter and 3 ft. long, with an accelerating-grid voltage of 15,000 and a grid-to-plate spacing (between planes) of about 6 cm., would conduct 1,000 amperes. The emitter-to-plate loss could be made small - of the order of 10 kw. With an accelerating-grid current equal to 0.5 per cent of the total current, this grid loss would be 75 kw. The energy required to produce the necessary electron emission from the thoriated tungsten emitting surface is of the order of 10 kw. The temperature of the grids and plates must be maintained below that of appreciable electron emission due to both thermal emission and the Schottky effect. With tungsten surfaces this consideration allows an operating temperature of about 1100 degrees K. Additional heat-radiating surfaces, or the introduction of a circulating cooling medium, or the conduction of heat through an insulator, are means by which the grid loss can be dissipated. The spacing between accelerating grid and plate is such that 1,000,000 volts should be safely withstood between them. The power capacity of the switch is 1,000,000 kilowatts and the energy loss is of the order of 0.01 per cent.

It is recognized that the calculations above are for a switch of unprecedented power capacity and insulation strength, and that the problem is simpler for lower power and voltage ratings. It is also recognized that the compactness or high current density suggested by the above calculations is of the order of which such a switching device is ultimately capable. Even with a more immediately attainable compactness, one-tenth or less than that suggested above, this switch would still be far more practical and advantageous by comparison than the present highly-developed high-power and voltage alternating-current switches. A current density of 0.0125 ampere per square centimeter would require an accelerating voltage of 6600 volts with a grid-to-plate spacing of 10 centimeters (calculated between thin parallel planes for uniform current density.) Such a lowered current density could be more effectively focused: for a given total current the losses are reduced because of both the lower grid voltage and current, and the loss radiating surfaces increased by a factor of ten. It may prove desirable to reduce the insulation requirements on a given switch by operating two switches in cascade. This arrangement is seen to be stable, the voltage drop across each so adjusting itself relative to the other that their currents are the same.

It is evident from the theory of this switch that current can be conducted by it in only one direction. The use of two such switches - one connected in the reverse sense from the other - across the gap in the high-voltage line would permit two-way conduction. Such a double arrangement of switching elements would also be capable of serving as an alternating-current switch.

Switches of the type described above may be used to accomplish the commutation functions in the direct-current machines described in Chapter II. The particular circuit connections involved in this electronic commutation have in general been indicated. Where not only the normal one-way valve action of these electronic switches is desired, but also the positive control afforded by the control grid for the interruption of current at any time, it may prove desirable in many machinery applications to provide a pilot commutator which supplies the proper voltage to the control grid. Thus, by means of a low-voltage, low-power commutator, the current, voltage, and power output of a large power machine may be closely regulated.

In certain switching applications where small currents are required it may be desirable to dispense with an accelerating grid, the current density being kept sufficiently low so as not to require an undue emitter-to-plate voltage. Such a switch is illustrated in Fig. 50, which shows a small substation switch for controlling small blocks of power removed from a large high-, direct-voltage power line.

In the above switches the power for the heating element of the emitter may be conveniently and efficiently supplied at the necessary high potential by a vacuum-insulated transformer such as is shown in Fig. 51. The primary and core are maintained at ground potential; the secondary is attached to the high-voltage part and vacuum-insulated for full voltage from the primary and core. The closed magnetic circuit makes for high efficiency and low reactance drop. This idea of vacuum-insulated transformers was developed during this investigation; some of its possibilities for high-voltage, large power transformers have been examined.

FIGURE 47

VACUUM ELECTRONIC POWER SWITCH
SHOWING CONCENTRIC ARRANGEMENT OF ELEMENTS.

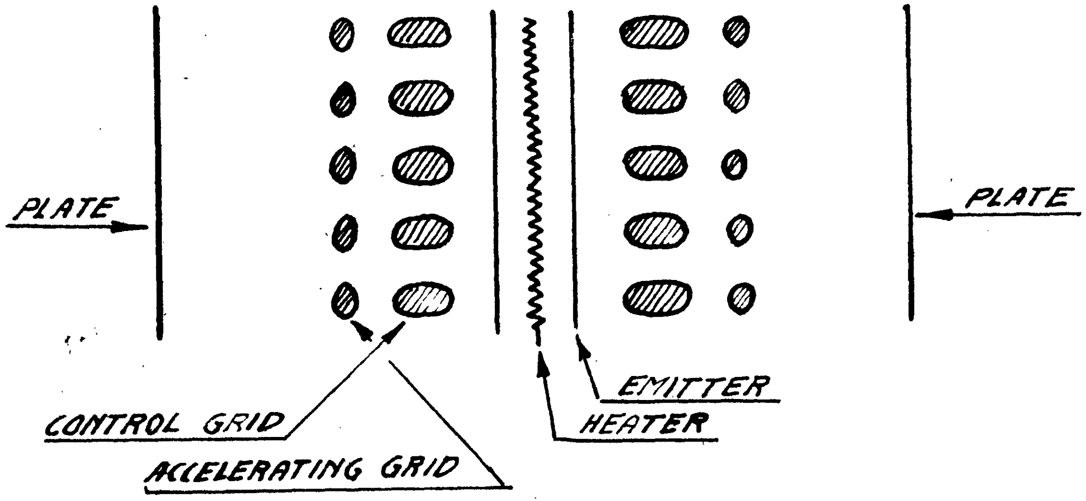


FIGURE 48

FOCUSSING EFFECT OF CONTROL GRID

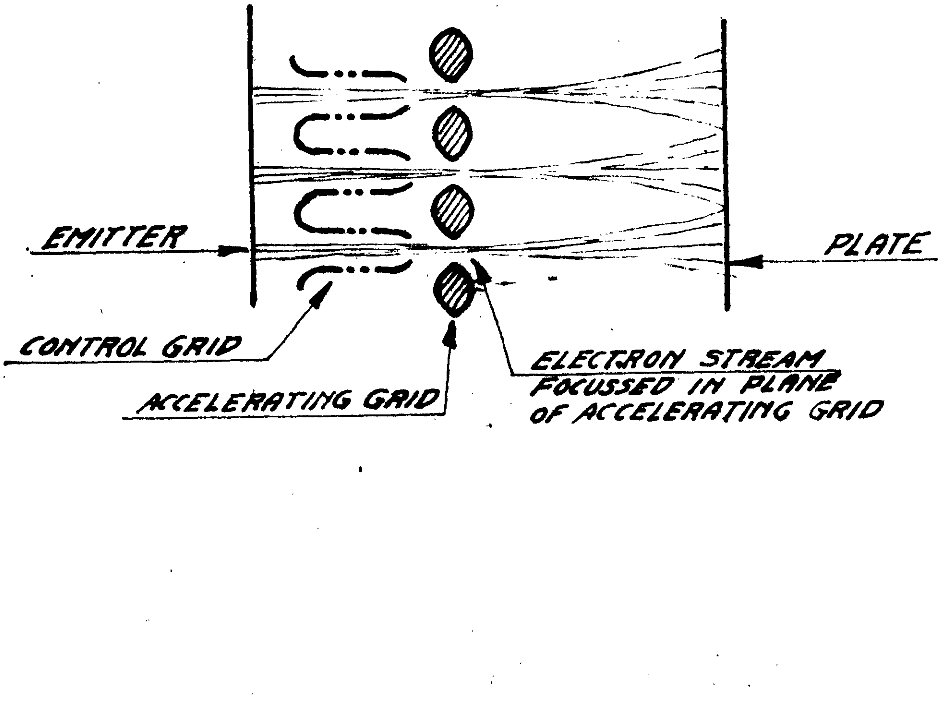


FIGURE 49

DIRECT HIGH VOLTAGE POWER TRANSMISSION CIRCUIT

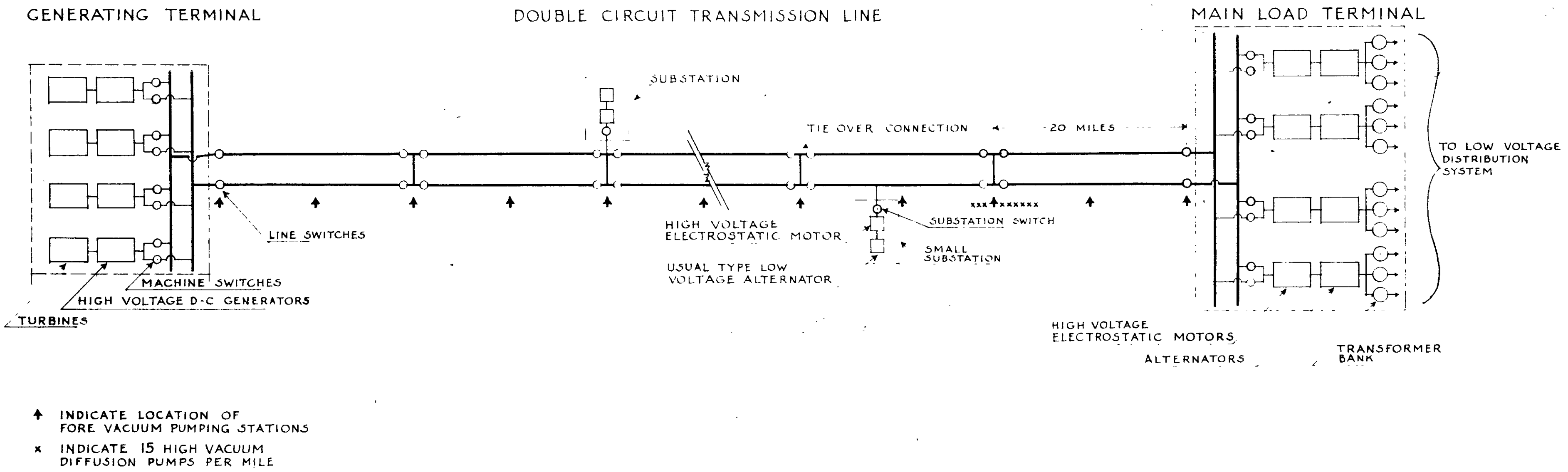
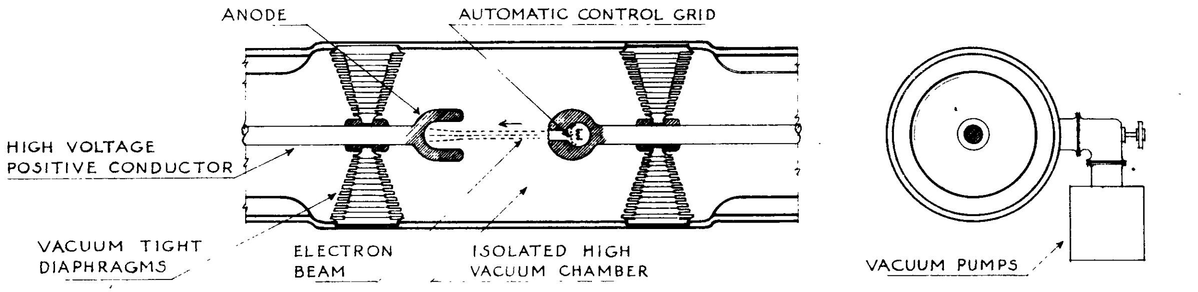


FIGURE 50

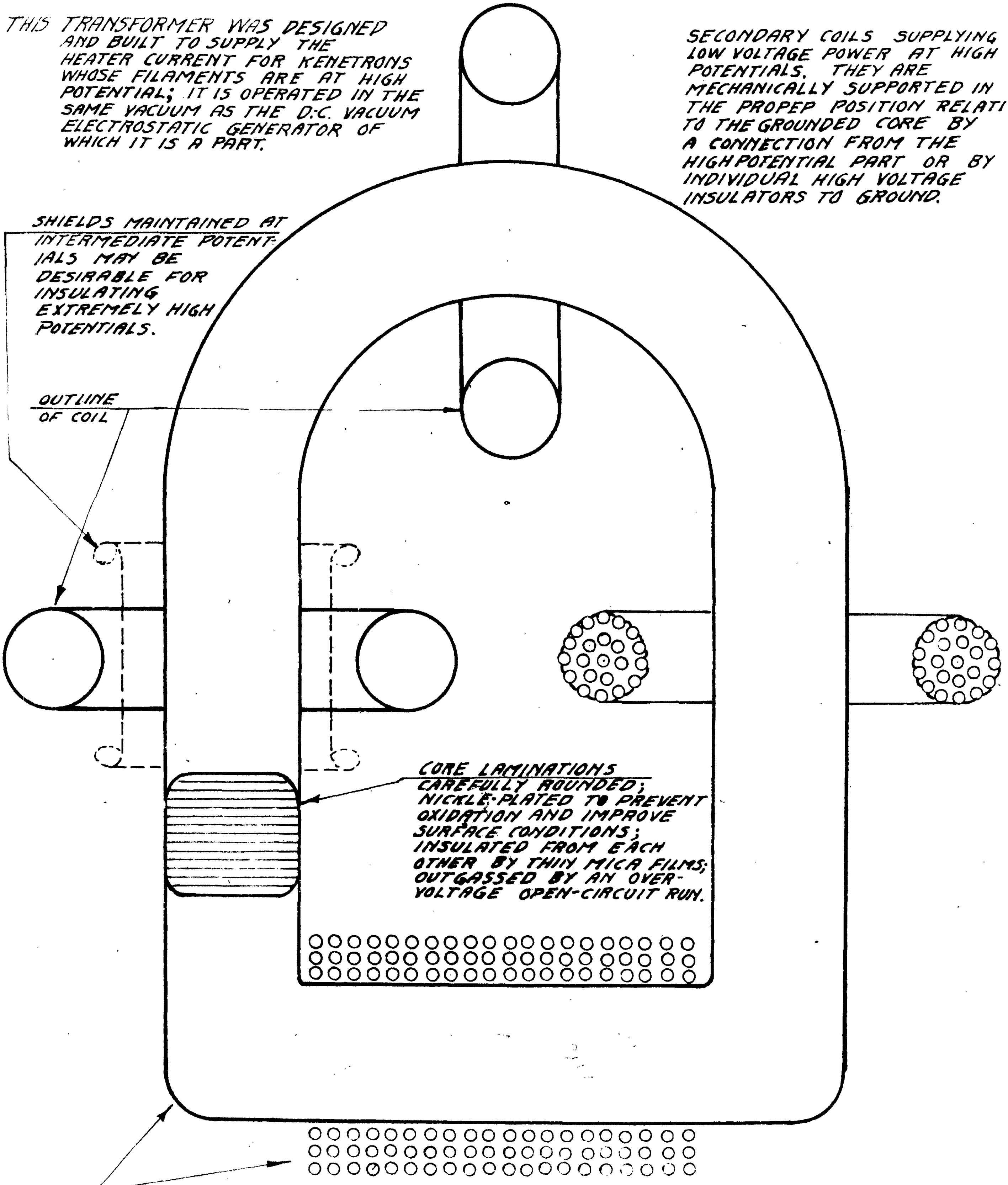
DIRECT HIGH VOLTAGE SUBSTATION SWITCH



J G TRUMP
MASS INST TECH.
1933.

FIGURE 51

VACUUM INSULATED TRANSFORMER



THIS TRANSFORMER WAS DESIGNED AND BUILT TO SUPPLY THE HEATER CURRENT FOR KENETRONS WHOSE FILAMENTS ARE AT HIGH POTENTIAL; IT IS OPERATED IN THE SAME VACUUM AS THE D-C VACUUM ELECTROSTATIC GENERATOR OF WHICH IT IS A PART.

SECONDARY COILS SUPPLYING LOW VOLTAGE POWER AT HIGH POTENTIALS. THEY ARE MECHANICALLY SUPPORTED IN THE PROPEP POSITION RELATIVE TO THE GROUNDED CORE BY A CONNECTION FROM THE HIGH POTENTIAL PART OR BY INDIVIDUAL HIGH VOLTAGE INSULATORS TO GROUND.

SHIELDS MAINTAINED AT INTERMEDIATE POTENTIALS MAY BE DESIRABLE FOR INSULATING EXTREMELY HIGH POTENTIALS.

OUTLINE OF COIL

CORE LAMINATIONS CAREFULLY ROUNDED; NICKLE-PLATED TO PREVENT OXIDATION AND IMPROVE SURFACE CONDITIONS; INSULATED FROM EACH OTHER BY THIN MICA FILMS; OUTGASSED BY AN OVER-VOLTAGE OPEN-CIRCUIT RUN.

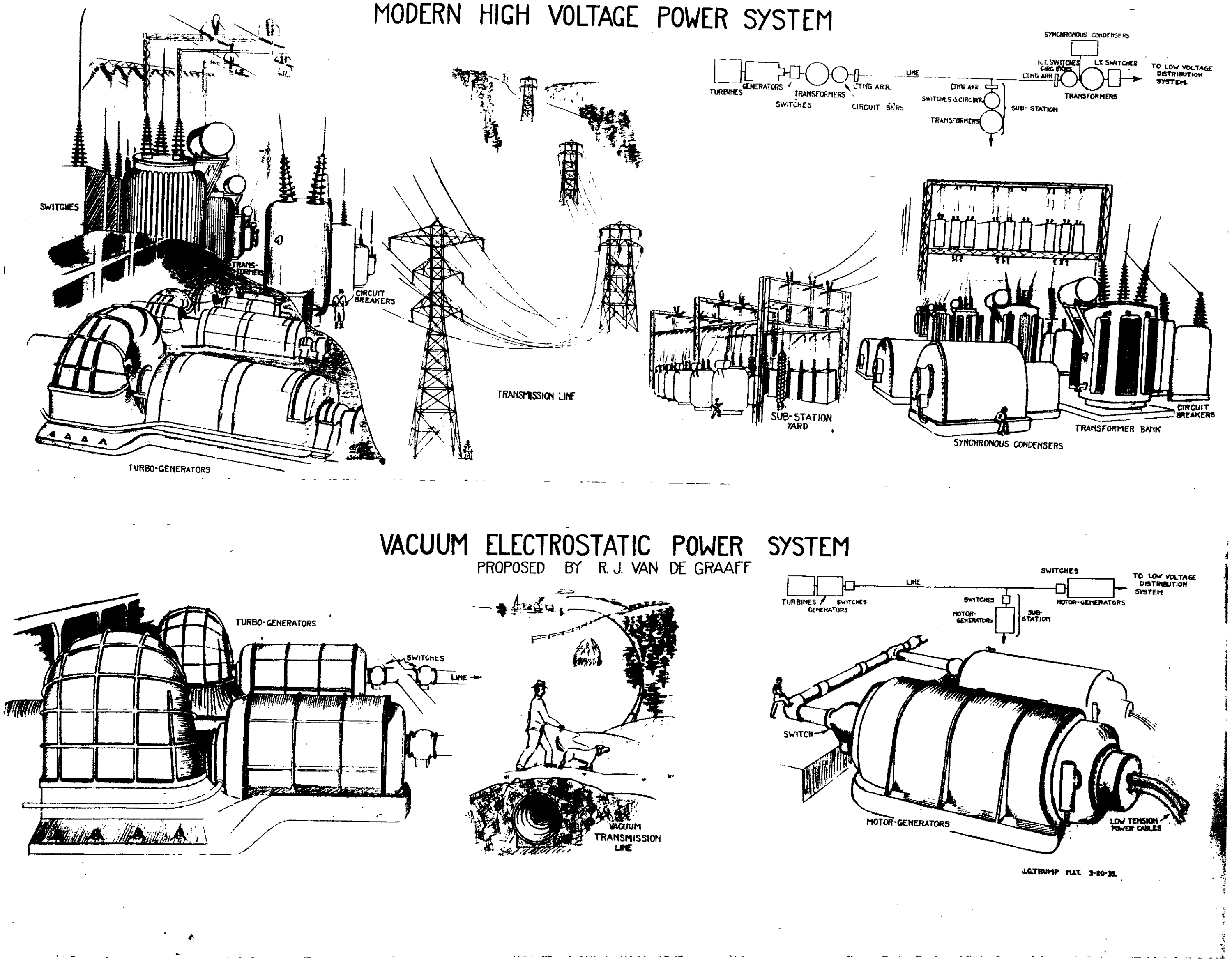
CORE AND PRIMARY WINDING MAINTAINED AT GROUND POTENTIAL.

WINDINGS MADE OF ALUMINUM OR OF NICKLE WIRE, INSULATED BY MICA OR PIREX, OUTGASSED BY HEATING.

VACUUM INSULATED TRANSFORMERS FOR OTBER APPLICATIONS HAVE BEEN DEVISED DURING THIS INVESTIGATION.

J.G. TRUMP
MIT 1933

FIGURE 52



MODERN HIGH VOLTAGE POWER SYSTEM

VACUUM ELECTROSTATIC POWER SYSTEM
PROPOSED BY R. J. VAN DE GRAAFF

J.G.TRUMP M.I.T. 3-20-33.

CHAPTER IX

VACUUM ELECTROSTATIC POWER SYSTEM

This investigation of high vacuum as an insulating medium, and of its application to the problems of electric power engineering, has shown the technical and economic feasibility of a new type of power system, capable of all the functions of modern power systems, but possessing advantages in power capacity, range of transmission, efficiency, and simplicity not even remotely approached by the power systems of today.

The new system contemplates the generation in vacuum by electrostatic machines of large amounts of electric power at hitherto unattainable direct voltages of the order of a million, the transmission of this power at these high voltages over a vacuum-insulated transmission line, and the conversion of this power at the receiving end back to mechanical form by vacuum electrostatic motors operating directly on full line voltage. The motors may drive the load directly, or they may drive electrostatic alternating- or direct-current generators, or they may drive alternators of the conventional type, thus delivering power to existing local distribution systems without any alteration of these systems.

A conservative comparison of the proposed direct-, high-voltage power system with the conventional system of today brings to light many outstanding points of difference in favor of the new system.

The vacuum electrostatic generators and motors contemplated for this power system and described herein are inherently high-voltage machines characterized by unusually high efficiencies, and in their ultimate form capable of much higher power concentration than modern electromagnetic power machines.

By the use of hitherto unattainable direct-current voltages of a million or more, the transmission losses are reduced to a small fraction of present-day values. This consideration, together with the absence of stability problems in direct-current systems, results in the removal of the distance limitation from electrical power transmission and makes possible a new era in the utilization of electrical power. It should become possible, for example, to deliver power to centers of consumption remotely situated with respect to potential power sources such as coal mines or water falls. Furthermore, it appears that the system will lend itself to the tapping off of small blocks of power at less cost than in prevailing systems, thus making feasible the supply of small communities and areas which could now be served only at prohibitive rates.

It has been impractical until recently to increase beyond 220,000 the operating voltages of modern high-power transmission lines. While increase in operating voltage to 275,000 has recently been proposed,* it is evident that alternating-current systems are not inherently high-voltage systems, and a definite economic and technical saturation effect would seem to render impossible the future attainment of the operating voltages contemplated for the vacuum electrostatic power system.

As far as can be seen in terms of present rates of power consumption, the power-transmitting capacity of the proposed system is limited

---

* Boulder Dam Power Project.

only by the power available at the source and by the load demand. Present power systems are limited by the factors already mentioned, as well as by the problem of system stability inherent in alternating-current power systems.

The proposed high-, direct-voltage power system is believed to be inherently capable of greater reliability than present systems for reasons set forth below.

The proposed system shows advantages in simplicity and economy over present systems. Involving, as it does, but a single high-voltage conductor surrounded by a grounded return with its terminal apparatus directly connected to the line, it is evidently far simpler and far more compact than present systems. The concentric conductor arrangement of the new system, which may be carried on or below the surface of a narrow strip of ground, is preferable to the cumbrous overhead system with its necessarily extensive right of way. The new type of line can be carried with perfect safety beside railroads or highways, thus making unnecessary a new right-of-way with the usual expense of land takings and land damages. Furthermore, it can be carried directly into urban areas.

A consideration of the above factors would indicate that such a system would not only offer unparalleled advantages in capacity and distance of power transmission, but would require far less plant investment and would be inherently capable of far greater economy of operation and reliability than equivalent systems of today. Fig. 52 illustrates pictorially some of the differences between the proposed and the present power systems.

The following comparative analysis of the proposed and present power systems covers in a more complete and quantitative way the power capacity, transmission distance, cost, and inherent reliability of the two systems. It contains the results of an investigation intended to bring out the relative merits of the two systems as applied to the recently-proposed St. Lawrence power project.

1. Power Capacity

There seems to be no theoretical or practical maximum power restriction for the vacuum electrostatic power system other than the limited power available at any one site and the economic demand for power.

The direct-voltage vacuum transmission line is inherently a high-power line and, without multiplication of circuits, appears to be capable of transmitting power of the order of millions of kilowatts with high efficiency.

Present electromagnetic power systems are restricted in the power they can handle by the fundamental problem of power stability, and by their inability, beyond a certain point, to meet increasing power requirements by increasing the operating voltage.

2. Transmission Distance

The vacuum electrostatic power system should be capable of transmitting practically unlimited amounts of power over substantially any terrestrial distance or area. To illustrate, calculations have been made for such a system operating at 5,000,000 volts and transmitting 1,000,000 kw. halfway around the world. A careful study has been made showing the practicability of vacuum transmission lines operating at 1,000,000 volts and transmitting 1,000,000 kw. a distance of 1000 miles with an energy loss of two and one-half per cent.

Present electromagnetic power systems are seriously limited in the transmission of large amounts of power over long distances by the necessity of maintaining a condition of stability between the sending and receiving ends of the transmission line, and by the necessary increase of energy loss with transmission distance. Although no such line exists at present, it is technically possible, by using the highest transmission voltage thus far developed, and with synchronous capacitance on the line at intervals, to transmit about 400,000 kw. over a double-circuit line for a distance of about 400 miles. While it is theoretically possible to extend such systems still further, the increased difficulty and expense of maintaining them free from interruptions, their low over-all efficiency, and the high capital investment would render such extended systems impractical.

3. Efficiency

The energy loss in vacuum electrostatic power machinery for large power generation and conversion purposes has been estimated to be about one per cent of the power rating of the machines. The energy loss in transmitting 1,000,000 kw. through a 1,000,000-volt, double-circuit vacuum transmission line a distance of 100 miles has been calculated as less than 0.25 per cent.

The energy loss in modern high-voltage generators of large capacity is about 4 per cent. The energy loss in the associated transformers to couple such generators to the transmission line adds another 0.5 per cent. The energy loss in the transmission line itself may be as much as 15 per cent of the power transmitted for the limited transmission distances of present practice. The line loss for 100 miles is usually from 4 per cent to 10 per cent, depending on the total transmission distance. Further losses are introduced by the auxiliary apparatus necessary to insure stability such as synchronous condensers, regulators, reactors, etc.

4. Cost

The estimated cost of a 100,000-kw., 1,000,000-volt vacuum electrostatic generator is about the same as, or less than, that of a 100,000-kw., 13,800-volt electromagnetic generator without step-up transformers.

The estimated cost by the St. Lawrence Power Survey Committee* of a 300-mile transmission line from the St. Lawrence to New York City of 1,000,000 h.p. capacity of $75,000,000. The estimated cost of a double-circuit, 1,000,000-volt vacuum transmission line for the same project, capable of even greater power capacity and far greater efficiency, is $20,000,000.

Vacuum electrostatic power systems would introduce other economies due to the elimination of devices essential to electromagnetic power systems such as transformers, synchronous condensers, voltage regulators, reactors, etc.

5. Reliability

It is believed that vacuum electrostatic power systems are

---

* Report of St. Lawrence Power Survey Committee.

ultimately capable of far greater reliability than present electromagnetic power systems. The various factors affecting the reliability of these systems will be discussed briefly point by point.

(a) Stability

An inherent characteristic of all alternating-current power systems is the tendency of small disturbances, normal switching operations, faults on the line, and the like, to cause oscillations and lack of synchronism between the sending and receiving ends of the transmission line with resultant service interruptions. The margin of stability decreases with increase in power transmitted or in transmission distance. In modern power systems this margin is somewhat extended by operating precariously in a region of unstable equilibrium, using synchronous condensers, high-speed exciters, quick-acting circuit breakers, and other special equipment tending both to stiffen the system against disturbances and to reduce the duration of the disturbances. The system stability is the greatest difficulty in present systems in maintaining continuity of service.

Vacuum electrostatic power systems, being direct-current power systems, would have no such major stability problem.

(b) Lightning

Present overhead power systems are subject to direct strokes and to induced lightning potentials which precipitate faults between lines, flashover to ground, etc., and thus cause circuit interruptions.

Vacuum electrostatic power lines and equipment, being completely enclosed in a grounded metallic container, are not subject to lightning.

(c) Wind, Snow, Sleet, Mechanical Failure

Overhead power lines must be capable of withstanding enormous variable loads such as wind, snow, and sleet. Mechanical failure due to these causes is still a serious cause of circuit interruptions.

The high voltage conductor of vacuum transmission lines would not be exposed to the elements in the same way, and hence would not be subjected to this form of failure.

(d) Corona

Corona is the cause of energy loss on high-voltage transmission lines. At high altitudes it occurs at lower voltages. It is the factor which limits the maximum voltage at which power can be transmitted in air. To transmit power through air at 500,000 volts to ground without undue corona would require hollow conductors about 5 in. in diameter. Loss of reliability due to the increased weight of the conductor, increased wind and snow loads, as well as stability considerations such as the increased reactance due to the large conductor spacing renders such voltages impractical. In power machinery corona causes deterioration of insulating material and subsequent loss of insulation strength.

Vacuum transmission lines would have no corona loss nor corona phenomena.

(e) Interconnections

Interconnections in alternating-current power systems are effective in increasing the reliability and flexibility of the component parts. The problem of stability becomes extremely complex in such interconnected systems. It is recognized that the stabilizing effect of one part of the system upon an interconnected portion electrically remote may be small and even negligible.

There is every reason to believe that interconnections in direct-current power systems will be effective in increasing the reliability of the component parts, however remote. The increase in reliability may be accurately predicted.

(f) Insulation Strength

High-voltage power lines in air must be adequately insulated from ground and each other by insulator strings supported on steel towers. These strings are subject to electrical deterioration due to dust, birds, mechanical failure, etc.

In direct-current vacuum transmission lines one conductor must be insulated from the enclosing evacuated metallic shell. The voltage gradients involved can be precisely calculated and the line designed for the required insulation strength. Methods have been devised which, with further development, are expected to insure high vacuum with extreme reliability.

(g) Relay Protection

The need for elaborate relay protection for three-phase power systems to protect generators, exciters, regulators, transformers, buses, lines, etc., and the resultant increased possibility of faulty relay operation has in itself proved an important cause of circuit interruptions in present power systems.

On the other hand, it appears that the protective equipment in the proposed vacuum electrostatic systems would be much more simple and hence capable in itself of greater reliability.

(h) Tie-overs

The number of tie-overs along double- or triple-circuit transmission lines is few because of the expensive overhead work, switch gear, and circuit breakers required.

The number of tie-overs along vacuum transmission lines in parallel may be frequent because of the simplicity of the apparatus involved. This results in greatly improved reliability.

6. Flexibility

In present alternating-current systems it is uneconomical to tap small amounts of power from high-voltage transmission lines for distribution purposes because of the expensive step-down and switching apparatus required. In high-voltage electrostatic power systems it seems economically and technically possible to tap off relatively small amounts of power from the line at frequent intervals.

High-voltage alternating-current power lines must be confined to open country, and the power must be transformed to reduced voltage before it can be brought to densely-populated areas. Vacuum transmission lines operating at millions of volts may, if necessary, pass directly through any densely-populated area. It is feasible, for example, to carry a vacuum transmission line operating at a million volts or more, directly down the length of Manhattan in New York City.

The power capacity of alternating-current power systems cannot be sensibly increased after installation without increasing both the capacity of the terminal apparatus and the power capacity of the transmission line in the same ratio. The power capacity of vacuum electrostatic power systems can, after installation, be increased very considerably by increasing the capacity of the terminal apparatus without changes in the transmission line, since high-voltage vacuum transmission lines have inherently extremely high power capacity, generally greatly in excess of the terminal apparatus.

7. Simplicity

Modern alternating-current power systems have become extremely elaborate and complex in an effort to provide for the many contingencies which may arise to cause circuit interruptions, and also because of the complexities inherent in electromagnetic machinery. The component apparatus itself is usually heavy and bulky, subject to deterioration, and necessarily designed with large factors of safety.

Vacuum electrostatic power systems are characterized by simplicity due to the relative ease and directness with which high-voltage, direct-current power can be generated and converted by electrostatic apparatus, and due to the simplicities inherent in direct-current power systems. Vacuum electrostatic machinery is further characterized by relative lightness and compactness due to the fundamental nature of electrostatic forces and effects and to the elimination of irrelevant matter.

8. Safety

Modern high-voltage systems are a source of danger to human life by accidental shock and by flashover.

High-voltage vacuum electrostatic power systems are relatively safe, since all high-voltage parts are completely enclosed in a grounded metallic case, the system appearing as a neutral body when viewed from the exterior.

9. Interference

Alternating-current power systems cause serious telephone, telegraph, and radio signal interference which is often difficult and expensive to overcome. High-voltage power transmission lines with their attendant large right of way offer a physical interference with the development of the surrounding areas.

Vacuum electrostatic direct-current power systems are free from these difficulties.

APPENDIX A

EFFECTIVENESS OF AREA UTILIZATION WHEN CAPACITANCE VARIATION IS SINUSOIDAL

This analysis is for the purpose of determining the effectiveness of plate-area utilization when the capacitance variation with angle between the rotor and stator of an electrostatic machine is sinusoidal over what it is when the variation is uniform.

Referring to Fig. 5~~4~~3?, for the sinusoidal variation we have

$$\frac{dA}{d\phi} = \frac{r_1^2-(r_2+X)^2}{2} = K \sin \phi$$

and

$$A_s = K\int_0^{\pi} \sin \phi \; d\,\phi = 2K$$

when

$$\phi = \frac{\pi}{2}\,, \qquad \frac{dA}{d\phi} = \frac{r_1^2-r_2^2}{2} = K$$

and

$$A_s = r_1^2-r_2^2$$

The area of the sector from which this sinusoidally-varying area has been taken is

$$A_u = \frac{r_1^2-r_2^2}{2} \int_0^{\pi} d\phi = \frac{\pi}{2}\,(r_1^2-r_2^2)$$

The ratio of the effectiveness of area utilization in the case of sinusoidal and of uniform capacitance variation is therefore:

$$\frac{A_s}{A_u} = \frac{2}{\pi}$$

APPENDIX B

A NEW NULL METHOD OF DETERMINING VOLTAGE GRADIENT DISTRIBUTION ALONG ELECTRODE SURFACES

This experimental method of voltage gradient determination at electrode surfaces grew out of the necessity for a convenient and accurate means of studying the voltage gradient distribution along the edges of the approaching rotor and stator plates of electrostatic power machinery. The complexity of the geometrical configuration eliminated the possibility of an easy analytical attack, and the necessity for accuracy, flexibility of electrode arrangement, and rapidity of measurement led away from the standard engineering methods and toward the more refined and direct methods of physics.

As is well known, the charge fixed on an increment of surface is proportional to the voltage gradient at that point. By measuring successively the charges fixed on a series of insulated probe areas along the electrode surface, the voltage gradient distribution along that surface can be determined. The charge stored on a probe was measured by spilling it, simultaneously with a charge of the opposite sign from a small condenser charged with a known voltage, into a Lindemann electrometer, the known charge being altered by a potentiometer arrangement until no resultant kick of the needle indicated both charges were equal. The proper balancing voltage for any one probe can usually be obtained within six trials, each taking but a few seconds. For an electrode surface with twenty probes the gradient distribution can be taken in as many minutes; and when, as in this case, the variation of gradient distribution with electrode separation is desired, a whole family of distribution curves may be obtained in a morning's work. The actual experimental set-up and results will now be briefly described.

It was desired to measure the gradient distribution along the edges of approaching condenser plates of the interleaving type with a view to determining the edge contour which would result in the lowest ratio of maximum edge gradient to the normal gradient between parallel faces of interleaved plates. For this purpose an enlarged section of three stator and two rotor plates was constructed of wood with removable round plate edges, the surfaces being covered with tin foil. The arrangement was such that the rotor and stator could easily be moved into each other so as to interleave; with more difficulty the plate separation could be changed. A flexible celluloid sheet conformable by tension to the plate-edge contour covered a portion of the middle stator plate. This sheet was covered with tin foil on the outside, and had eighteen small insulated tin-foil probes of equal area, these probes extending from the tip of the rounded edge to a point well along the parallel side of the plate. Contact with any one probe could be effected by a switch within the hollow middle plate, the switch simultaneously short circuiting all remaining probes to the plate itself. The contacted probe was thus connected by means of a well-shielded lead to a Lindemann electrometer, as shown in Fig. 54. The experimental procedure was as follows: The electrometer grounding key was opened and the operating key suddenly depressed. This released nearly simultaneously both the charge which had been fixed on the probe and the charge which had been stored in the fixed condenser. These charges mixed, the net amount charging the electrometer. The voltage V on the fixed condenser was then adjusted until no electrometer kick indicated the charges were equal.

The flexible celluloid strip was 0.01 in. thick and held the arrangement of probes and conducting coating (both of 0.0007-in. tin foil) fastened to it with ceresin. One end of each probe strip was passed through a slit in the celluloid, where it was attached to a flexible enamelled wire connecting to the switch. The arrangement of probes could be calibrated both for relative values of voltage gradient (taking into account the differences in probe area) and for absolute values of voltage gradient if the area of one probe is accurately known. This can be done by unloosing the celluloid strip from the contour edge and holding it plane and parallel to a plane electrode a known distance away with the known positive voltage impressed on it. With this method of calibration it was estimated that the over-all accuracy of the voltage gradient determination was within two per cent.

The results of the voltage-gradient distribution studies for two different edge contours (the circular edge and the circular-bulbous edge) are shown in Figs. 29 and 30. It is seen for the particular ratio of plate thickness to separation of the experiment that the ratio of the highest gradient to the parallel-plate gradient is 1.7 in both cases. This indicates that this particular plate-thickness-to-separation ratio is close to that critical value below which the bulbous edge is the more desirable, and above which the simple circular edge becomes more desirable. A study of the curves indicates that more complex contours than those studied would not be compensated by material improvement in the voltage-gradient ratio.

The general advantages of the above experimental method of gradient-distribution studies may be summarized as follows:

1. A rapid and convenient method of measuring voltage-gradient distribution along complex electrode surfaces.

2. A method particularly adapted for complete studies involving a family of distribution curves showing the effect of variation of electrode separation, etc.

3. A method showing a higher degree of sensitivity than previous standard methods.

4. A null method characterized by high accuracy and ease of calibration.

FIGURE 53.

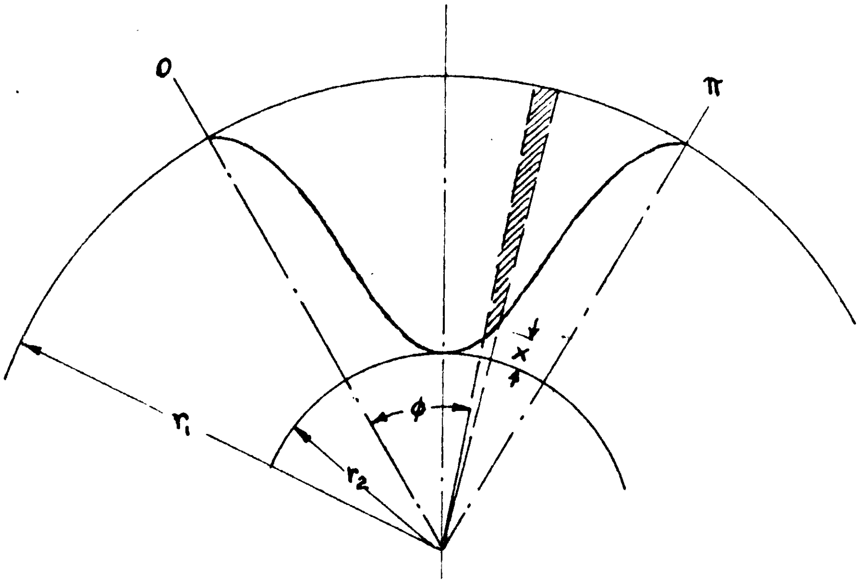
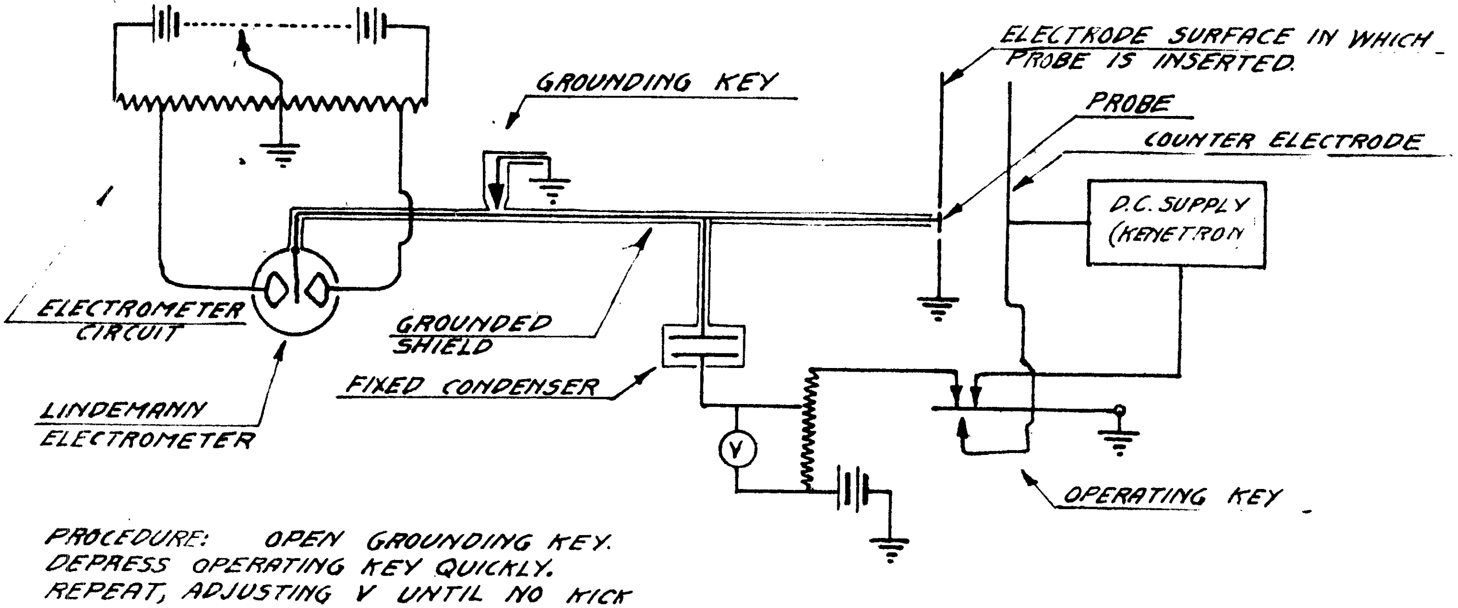


FIGURE 54
ELECTROMETER AND PROBE SET-UP FOR VOLTAGE GRADIENT DETERMINATIONS.



PROCEDURE: OPEN GROUNDING KEY. DEPRESS OPERATING KEY QUICKLY. REPEAT, ADJUSTING V UNTIL NO KICK IS OBTAINED IN ELECTROMETER.