A PORTABLE 750 KILOVOLT VAN DE GRAAFF GENERATOR

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A PORTABLE 750 KILOVOLT VAN DE GRAAFF GENERATOR

Historical Background

The basic idea of a belt type of generator was formulated in 1890 by Lord Kelvin (6, p. 152); it was 1929 before Van de Graaff (5, pp. 153-154) produced the first working model, an 80 kilovolt machine. Having successfully proved the method, Van de Graaff (5, pp. 761-776), in association with the Massachusetts Institute of Technology, projected the construction of an enormous belt machine at Round Hill, Massachusetts. This installation consisted of two identical units standing forty feet in height and having spherical electrodes fifteen feet in diameter. One sphere was charged positively to a potential of 2.4 million volts to ground, the other negatively to a potential of 2.7 million volts in respect to ground. These results were obtained under conditions of high atmospheric humidity.

It was early realized that an electrostatic machine of small dimensions might be made to operate in either a vacuum or compressed gas. It was difficult to obtain a good vacuum in a large system, so this method was abandoned in favor of pressurization. Herb (2, pp. 75-83) and his associates at the University of Wisconsin did much of the early work on pressurized machines.

The Van de Graaff generator has been developed as a very useful instrument for obtaining a monoenergetic beam of
charged particles when used in connection with an ion accelerator tube. Under construction at Los Alamos, New Mexico, at the time of this writing is expected to be the highest voltage Van de Graaff generator yet built (4, p. 1). This huge machine is designed to accelerate positive ions under high precision control to energies of about 12 million electron volts.

Operating Principles

This paper describes a relatively small and inexpensive air-insulated Van de Graaff generator. As shown in Figure 1, the generator consists of a high voltage electrode supported from ground on an insulating column and of a charge conveying system consisting of a high speed belt of insulating material for carrying charges to this electrode from ground potential.

At the grounded end a charge, shown as negative in the diagram, is sprayed on the belt from corona points directed at the lower pulley. This charge is supplied to the corona points by a power supply furnishing a direct current voltage adjustable from zero to about 10 kilovolts. The high voltage gradient in the vicinity of the points causes a local ionization of the air. This ionization allows conduction of the charge toward the pulley. The charge is
intercepted by the belt, giving the effect of spraying charge on the belt. The amount of charge sprayed on the belt in this manner is controlled by the voltage of the power supply. The belt transports the charge to the upper pulley where a similar arrangement may be used to remove the charge. For this generator a simple self-inducing arrangement replaces the power supply. The charge on the belt, on entering the hollow conductive terminal, has a negative potential relative to it, irrespective of the potential of the terminal to ground.

The upper pulley is insulated from the high voltage terminal and is charged to a potential negative to that of the terminal by means of corona points placed just below the point of tangency of the arriving belt. This difference of potential is utilized by placing other corona points just above the pulley where they are connected to the high voltage terminal. This results in ionization at the upper corona points and a continuous transfer of positive electric charge from terminal to moving belt which neutralizes the charge brought up and leaves a residue of positive charge. This charge is carried downward by the belt to the lower corona points where the positive charge is neutralized and negative charge sprayed on to initiate a new cycle. The addition of negative charges to the insulated terminal and the removal of positive charges leaves it highly negative.
in respect to ground. The terminal may be made positive in respect to ground by spraying positive charges on the belt at the lower pulley.

Design Considerations

The Van de Graaff generator described in this paper was designed to provide a portable high voltage source having a useful output current. It was designed to be relatively free from vibration and independent of atmospheric humidity. Portability required that the machine be of such width and height as to be wheeled through a three foot by seven foot doorway and of sturdy enough construction to withstand the "knocks" encountered by movable equipment. The size limitation determines the maximum potential obtainable, since, for an air insulated machine, the maximum potential depends upon the size and shape of the high voltage electrode and the length of the insulating support. The insulating column is designed to provide a voltage gradient not greater than 20 kv per inch, a gradient which Trump (3, p. 399) found to be near the maximum for successful operation.

At the desired voltage, the electric field at all points on the electrode surface must be below the ionizing value of approximately 25-30 kv/cm in air if serious corona
leakage is to be averted. Two hemispherical aluminum spinnings 5\(\frac{1}{4}\) cm. in diameter were on hand in the department for use in the construction of the generator. Considering a spherical electrode, the maximum potential to which it may be raised is determined as follows:

The charge \(Q\) on an isolated sphere of radius \(r\) is given by

\[ Q = CV \]

Eq.1

where

\(C\) = capacitance of body, and

\(V\) = voltage to which sphere is raised.

By Gauss's law,

\[ EA = 4\pi Q \]

Eq.2

where

\(E\) = electric field strength perpendicular to surface, and

\(A = 4\pi r^2 = \text{area of sphere.}\)

Using electrostatic units, \(C = r\).

Substituting this value and Eq.1 into Eq.2,

\[ V = Er \]

Eq.3

If we use \(E\) equal to 25 kv/cm and 30 kv/cm, we obtain a maximum potential \(V\) equal to 675 kv and 810 kv respectively.

Added space for the pulley system was provided by placing an 16-inch long aluminum cylinder between the two hemispheres. This addition should have little effect upon the maximum potential as calculated for a spherical electrode, since the
radius of curvature at any point on the surface is not decreased.

The maximum amount of current that a Van de Graaff generator can deliver is proportional to the belt width and speed. The belt width and pulley diameters are in turn dependent upon the diameter of the insulating column. A Herculite\textsuperscript{1} insulating column having an outside diameter of 12 inches with \( \frac{1}{8} \)-inch walls was selected for this construction. It is large enough to accommodate a 9-1/2-inch charge carrying belt running on 4-1/2-inch pulleys, yet it is not so large as to destroy an unreasonable portion of the high voltage electrode where it enters.

In designing a piece of equipment having rapidly moving parts, vibration presents a serious problem. This problem is best attacked by heavy construction, well-balanced rotating parts, and, wherever possible, the isolation of moving parts from stationary members easily set into vibration. With a machine using high speed belts, such as a Van de Graaff generator, it is important that the belt be free from splices that would cause vibration.

A 0.6 horsepower, 110 volt, 3-phase, 945 or 1145 rpm, induction motor on hand in the department was chosen to drive the charge carrying system. This particular motor has

\textsuperscript{1} Trade name of General Electric Co., Coshocton, Ohio.
a well-balanced rotor and exhibits good construction throughout.

It has been found that a Van de Graaff generator can be made independent of humidity by totally enclosing the belt system and introducing a small amount of heat, preferably thermostatically controlled.

Safety to operating personnel requires remote operation of the principal controls and having these controls well grounded.

Construction

Figures 2 and 3 may be referred to in connection with the following discussion. The bed of the chassis is, for the most part, a welded framework of steel channel iron having three retractable castors attached. By retracting the castors the machine can be put into a more stable operating position, in that its center of gravity is lowered and any tendency to roll is eliminated. One swivel and two fixed castors were used to provide greater ease in guiding. Welded to the bed are four heavy angle iron posts which support the column assembly, which is otherwise isolated from the rest of the base assembly. This was considered an important factor in the elimination of vibration. After the bed was welded, the top of the column support posts and
750 KILOVOLT VAN DE GRAAFF GENERATOR

TEXTOLITE COLUMN

INNER SLEEVE FLANGE
OUTER SLEEVE FLANGE
CORK
TEXTOLITE
COLUMN CLAMP

SUPERSTRUCTURE

DRIVING PULLEY
DRIVE RETRACTABLE CASTOR ASSEMBLY
10,000 VOLT POWER SUPPLY
COLUMN SUPPORT POST
CHANNEL IRON BED

FIGURE 2
750 KILOVOLT VAN DE GRAAFF GENERATOR

LIGHT 4 PLY ENDLESS WOVEN BELT

TEXTOLITE COLUMN
1/2" OD x 3/4" ID

COLUMN CLAMP

COLUMN SUPPORTING POSTS

SELF ALIGNING BALL BEARINGS

CORONA ROD ADJUSTMENT

CORONA Rods

HEADER

RETRACTABLE CASTOR ASSEMBLY

FIGURE 3
bearing surfaces for the pulleys and motor were milled to insure smooth level surfaces for the mountings.

A framework of light angle iron having welded joints was built to carry a sheet metal covering of the base assembly. This structure was bolted to the bed by four bolts. Figure 4 is a photograph of the bed with the framework in place.

The sheet metal covering of the base assembly forms a semi air-tight enclosure which includes the column and the high voltage electrode to which heat is applied. This grounded enclosure protects the wiring from a discharge of the high voltage electrode and covers any sharp points of the base assembly that would give rise to corona. In addition, the enclosure covers all moving parts, thus providing personnel protection. Side panels of galvanized iron, which slide in folded aluminum runners, allow access to the base assembly. Two unlike metals give greater ease in sliding. Figure 10 shows a photograph of the generator with the sheet metal in place.

The Herculite column is mounted on the column posts and supports the top pulley assembly by a unique clamping arrangement. The rigidity of this assembly is important in suppressing vibration. Each of the two clamps consists essentially of an expandable sleeve placed on the inside of the column and a corresponding clamping sleeve placed around
the outside. A flange on each sleeve is bolted to a steel plate having a hole through which the charge carrying belt can pass. Using both the inside and outside sleeves, only the wall of the column is placed in compression, thus insuring a circular cross section of the column. Sheet cork 1/16-inch thick was placed between the sleeves and the Herculite to provide protection of the column and some vibration damping.

The sleeves were rolled to a cylinder from 1/4-inch thick flat stock and the ends temporarily tack-welded. The flange was then added by successively heating a portion of a strip of flat stock with an acetylene torch, bending it edgewise to the sleeve contour, and welding it progressively to the sleeve. The bearing surfaces of the sleeve and flange were trued in a lathe. The tacked seam was then reopened and lips welded along on each side of the seam. Bolts were fitted to the lips to apply a force to expand or contract the inner and outer sleeve respectively. Figures 5 and 6 show photographs taken on opposite sides of the machine showing the base assembly with the lower column clamp in place.

Two 3-inch channel iron posts are bolted to the upper steel mounting plate. The web of each channel section was milled out for a sliding rectangular block which carries a top pulley bearing. Stud bolts attached to the top of each
block provide vertical movement of the top pulley by which the tension on the charge carrying belt is adjusted. Set screws tapped through the webs of the channel iron clamp the bearing block in place as shown in Figure 3.

Shoulders were turned on a 1-1/8-inch shaft for discs of 3/8-inch steel plate. This assembly was fitted into a section of steel pipe and all joints welded. The assembly was then mounted between centers on the lathe. The pulley was turned to approximately 4-1/2 inches in diameter with a radial taper of 1/8 inch per foot over a distance 3 inches from each end to keep the belt in place.

Fafnir\(^2\) self-aligning ball bearings having a bore of 0.7874 inch, an outside diameter of 2.047 inches, and a width of 0.51 inch were used. Each bearing is set in a cavity turned in the sliding steel block. A threaded retainer plug holds the bearing in place, and felt oil rings in the block and plug are fitted to the shaft.

The charge conveying belt is driven by a 2-inch Tilton\(^3\) endless woven belt over pulleys having a step up ratio of \(\frac{4}{1}\). The driven pulley has a diameter of 3 inches which is near the minimum diameter for operation without slippage. The driving pulley is 12 inches in diameter which is about

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2. The Fafnir Bearing Co., Chicago, Ill.
the maximum diameter for the space available. This ratio
with a motor speed of 1145 rpm gives a belt speed of 90
feet per second.

The machine is equipped with a Tilton, light, 4-ply,
endless woven belt. This belt had been treated at the
factory with Tilton's compound number C13, which improves
the dielectric and corona properties of the belt. The belt
is 9-1/2 inches in width, 145 inches in endless length, and
approximately 1/16-inch in thickness.

The corona points were made by mounting phonograph
needles in screws tapped into a brass rod and spaced
1/2 inch apart. This allows adjustment of each point indi-
vidually. Each set of points was mounted on stud bolts to
allow adjustment of the corona points as a whole.

The theoretical maximum charge density which can be
placed on the belt is that which will give a gradient of
about 25 kv/cm; from Gauss's law this gives a charge of
4.4 x 10^-9 coulomb per square centimeter, assuming the
maximum gradient exists on both sides of each run of the
belt. At a belt speed of 90 feet per second and carrying
charges up and down, the maximum theoretical short circuit
current is 650 microamperes. As Bramhall (1, p. 20) and
Trump (3, p. 401) have observed, in practice the current
ranges around 35 per cent of the theoretical value; thus,
we have an expected current of 225 microamperes.
The complete circuit diagram for the generator is given in Figure 7. The power supply is a full-wave rectifier built around two 3B24 rectifier tubes and a 15 kv neon sign transformer with the secondary center-tapped to the case. Since it was desirable to build the generator so that either positive or negative charge could be sprayed on the belt, it was necessary to design the power supply so that either pole could be grounded. This required the use of a filament transformer with an isolated secondary. It was also necessary to feed the primary of the neon sign transformer from a 1 to 1 ratio, 10 kv isolation transformer. The components of the power supply were mounted upon a "Micarta" board which, in turn, was mounted upon four porcelain insulators. This was necessary since, in spraying positive charge, the neon transformer case is at 10 kv in respect to ground. A 0.5 megohm resistance was placed in series with the corona points to prevent sparking and consequent belt damage. The amount of charge sprayed on the belt is controlled by a 3 ampere variable transformer. Figure 8 shows a plot of the variation of power supply output against input for various loads. Figure 9 is a photograph of the power supply.

The variable transformer and switch, as well as switches controlling the tube filament current and motor relay, were mounted in a control box connected to the generator by a six-wire shielded cable, 25 feet in length.
750 KILOVOLT VAN DE GRAAFF GENERATOR
CIRCUIT DIAGRAM

GENERATOR

110 VOLT 3 PHASE MOTOR

THERMOSTAT

110 VOLT, 3 POLE, RELAY

T1: NEON SIGN TRANSFORMER; INPUT 115 V; OUTPUT 5 KV, 30 MA
T2: FILAMENT TRANSFORMER; INPUT 115 V; OUTPUT 5 V, SECONDARY INSULATED FOR 10 KV
T3: ISOLATION TRANSFORMER; INPUT 115 V; OUTPUT 115 V, SECONDARY INSULATED FOR 10 KV
T4: VARIABLE TRANSFORMER; INPUT 115 V; OUTPUT 0-135 V, 3 AMPS.
S1, S2, S3, S4: SWITCHES; SINGLE-POLE, SINGLE-THROW
S: MICROSWITCH; SINGLE-POLE, NORMALLY CLOSED
R: RESISTOR, 0.5 MEGOHM
F1, F2, F3: FUSES, 115 V, 15 AMPS.
P1, P2, P3: PANEL LAMP, 115 V

CONTROL PANEL

OUTLINE OF CHASSIS

WIRE SHIELDED CABLE

FIGURE 7
POWER SUPPLY PERFORMANCE CURVES

Figure 8
This provides protection of the operator from the high voltage.

The heater circuit was designed to use calrod heaters of the screw-in type. The heater was placed under the Herculite column. The heat would be circulated in the column and high voltage electrode by the moving belt and convection. The heat is necessary to keep the belt and Herculite column dry in order to maintain rated dielectric properties. The thermostat for the heater circuit, a bellows disc commonly used in chicken brooders, actuates a microswitch. The main switch controlling the heater is placed on the end of the generator.

The sheet metal housing of the top pulley system forms the high voltage electrode. The cylindrical mid-section of the electrode was made from a sheet of aluminum, the ends joined by a flush folded seam. The hole for the entry of the Herculite column is centered on the seam and destroys much of it; the remaining portions on each side of the column are held by trunk latches. The point of column entry is electrically the weakest region on the terminal. This was improved by an inward roll of the aluminum edge of the column hole to a radius of curvature of 1/2 inch. The cylinder is held to the top pulley assembly by four micarta blocks as can be seen in Figure 2.

The generator with the sheet metal in place left the
column with a metal to metal insulating distance of 42-1/2 inches. If the high voltage electrode were at 750 kv, the column would experience a potential gradient of 17.6 kv per inch, well within allowable design considerations. Figure 10 is a photograph of the completed generator and control box.

Preliminary Testing

At the time of this writing the Tilton endless belt had not arrived, and it was necessary to construct a paper charge carrying belt. Building paper was used. This consists of two sheets of tough brown Kraft paper bonded together with asphalt. The ends of the paper were joined in a V-shaped splice, lapped about 3 inches, and cemented with a special rubber cement. The paper belt seems to hold up well and to exhibit very good charge carrying ability, although it is somewhat difficult to keep it centered on the pulleys and the splice causes noisy operation. Excessive vibration was set up in the sheet metal housing, especially the galvanized sheet forming the floor of the base assembly. Because of this vibration, the motor was held at its slow speed. The endless woven belt will, no doubt, greatly aid in the elimination of vibration. The coating of the interior of the sheet metal enclosure and calking of joints with
sound absorbing material should decrease the noise.

No accurate method was available for measuring the potential developed on the high voltage electrode. Spark discharges about 2-1/2 feet in length were obtained between a sharp point and the high voltage electrode. Discharges in rapid succession were obtained from the curved bottom of a large metal water pitcher held 13-1/2 inches from the high voltage electrode. The potential was estimated, very roughly, to be about 600 kv or better, with the discharge point on the sphere dependent on the nearest or sharpest ground point. With nearby ground removed, the voltage would build up until corona to the room ceiling or near the electrode column junction was observed. This potential was estimated to be at or near the design value.

The short circuit current of the generator was measured by connecting the high voltage electrode through a microammeter to ground. A current of 170 microamperes was obtained with the electrode charged positively and the corona points at a potential of 8.6 kv. With another power supply on hand in the department a potential of 9 kv was supplied to the corona points, and a current of 200 microamperes was observed. This is an impressive current considering the paper belt, the low belt speed, limited adjustment of charge spraying points, and no control of humidity. With negative charge sprayed on the belt the observed short
circuit current was found to be very unsteady, varying from zero to 140 microamperes. This was caused by positive point corona from irregularities on the inner sleeve of the lower column clamp. The amount of charge lost in this manner varied as the belt shifted upon the pulleys. This effect could be corrected by removal of the sharp irregularities within the sleeve; and by using a narrower, more true running belt. By employing the endless belt and making minor adjustments, the operation of the generator can be greatly improved.

Conclusion

This generator is designed primarily as a portable high voltage demonstration unit. However, it has sufficient current output to provide the potential for an X-ray tube or positive ion accelerator tube. In connection with this later application, the nuclear reactions,

\[ _1^2H^2 + _1^2H^2 \rightarrow _2^4He^3 + _0^n + 3.28 \text{ Mev} \]

\[ _1^3H^3 + _1^2H^2 \rightarrow _2^4He^4 + _0^n + 17.6 \text{ Mev} \]

can be triggered by low energy bombarding particles.
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