Van de Graaff Generator

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Abstract

In this work it was developed a Van de Graaff generator that we design and built and that is intended to be used in secondary schools for teaching basic principles of electrostatics, electromagnetic as well as a number of other applications.

Today many schools laboratories and museums use this kind of generator for electrostatic demonstrations.

Electrostatics was first noticed by the Greek philosopher Thales, who discovered that amber attracted light objects when rubbed. For centuries this phenomenon was only considered a natural curiosity. It is a fact that extremely high voltages can be generated by friction of dissimilar substances. This fact is the base of electrostatic generators. The first known electrostatic generator was built in 1660 by the German experimenter, Otto von Guericke. The Van de Graaff generator was invented by Robert Jamison Van de Graaff, in the USA, by 1929, with the objective of generating high voltages for experiments in nuclear physics. Ancient electrostatic machines can be traced to the 1800's or before. The classical machine consists in a motorized insulating belt that transports charge to a hollow terminal. Inside the terminal the charge is collected by a comb close to the belt and transferred to the exterior surface of the terminal by the Faraday Effect. Charges are sprayed over the belt surface by another comb that is below, connected to an electronic DC high-voltage supply (motor). Guides and hints about the safe use of it in the classroom will be presented.

Keywords: Electrostatic machine, High Voltages, Van de Graaff generator.

1. Introduction

Electrostatics was first noticed sometime in 600 B.C. when the Greek philosopher Thales discovered that amber attracted light objects when rubbed. The phenomenon demonstrated a fundamental concept of electrostatics. It is an elementary physical fact that extremely high voltages can be generated by friction. [1]

This fact is the base concept of functioning of Van de Graff generators.

The Van de Graff generator is named after Dr. Robert J. Van de Graaff who patented his electrostatic generator in 1935. He developed this generator for studying the acceleration of charged particles to explore the atom.[2]

The Van de Graaff generator is an impressive electrostatic generator that is capable of producing enormously large static electric potentials. Giant Van de Graaff generators can produce millions of volts. More modest "class room" sized Van de Graaff generators typically produce 100,000 V to 500,000 V. [2]

This instrument marked several decades of contemporaneous science and was applied in several fields of physic, astrophysics, medical and industry. In the same way is very useful in school as a teaching device in electromagnetic and electrostatics.

The Van de Graaff generator, which was developed from the end of the 1920^{s} derives from a series 18th century electrostatic machines.[3]

In this work it will be present a generator build with the purpose of demonstrating basic principles of electrostatic in basic schools.

Some hints are presented to help in the construction of a Van de Graaf high voltage generator, and some demos that explore some physical facts and amazing exhibitions that can be performed with this device safely.

2. The Van de Graaff Machine Ancestors

Otto von Guericke, using a sulphur globe frictioned by hand, builds the first electrostatic generator in 1660. The globe could be removed and used as source on electricity experiments [4].

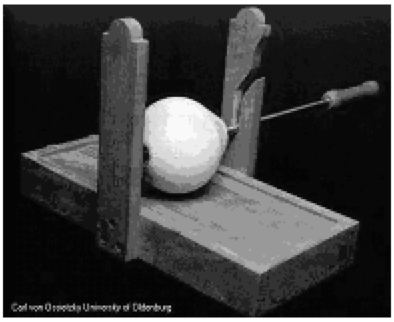

Figure 1. First electrical generator by Otto von Guericke.

Other electrostatic generators followed this one, between them generators by induction that also used friction.

In 1784, Walckiers constructed a machine with an horizontal looped silk strip passing over two wooden rollers.

The young physicist Augusto Righi in 1872 in his PhD thesis described an "induction electrometer" this apparatus was a perfect Van de Graaff generator. However, this machine had not been conceived as a generator but as a "charge magnifier" for investigating weak electrostatic phenomena.

Abraham Bennet in 1786 and William Nicholson in 1788 proposed their "multipliers". [3]

With these apparatus very small charges, too weak to be detected by a common electrometer, were "multiplied" by electrostatic induction until they could be measured. Righi was working in the same direction when he proposed his machine.

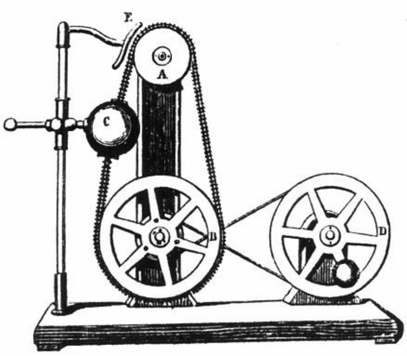

Figure 2. Righi`s apparatus.

A rubber belt carrying a large number of brass rings rotates on two metallic pulleys. The lower one, which is insulated, is connected with a crank and the upper one is grounded with a copper strip. Close to the belt, in the neighbourhood of the upper pulley, there is a small metallic conductor (the inductor) which is connected to the weakly charged object to be studied. The inductor charges one after another the brass rings of the belt which pass on the upper grounded pulley. Continuing their journey the rings enter a hollow insulated copper sphere, where they touch a third small metallic pulley fixed on its inside. Thus the charges of the rings accumulate on the external surface of the sphere. As the process continues the charges are continually added to the sphere. [3] This machine works in the same way as the Van de Graaff generator.

The endless-belt machines were never really popular and they could never compete with the disk induction generators of Holtz, Toepler, Voss, Carré, Wimshurst, Wommelsdorff and others.[3]

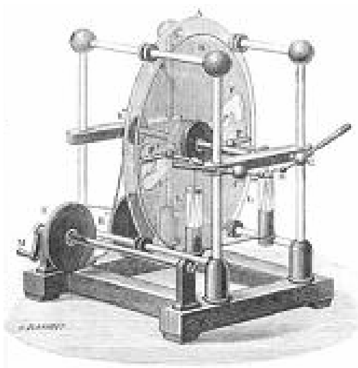

Figure 3. Holtz generator.

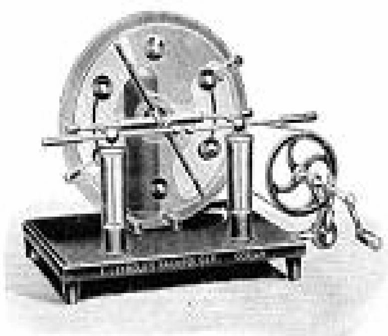

Figure 4. Voss generator.

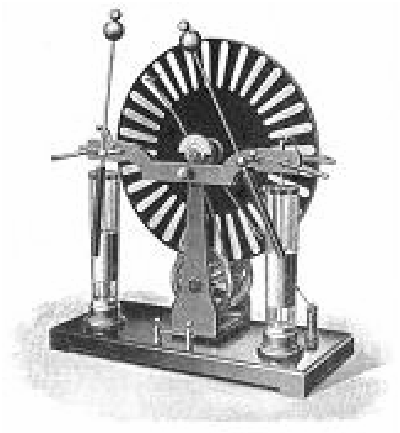

Figure 5. Wimshurst generator.

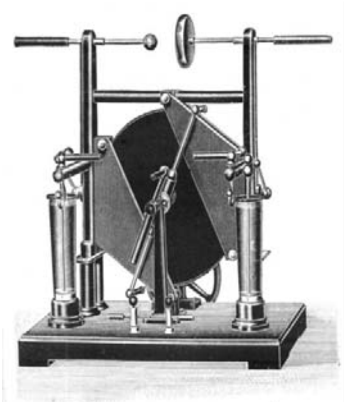

Figure 6. Wommelsdorff generator.

3. Motivation

In 1917 the British physicist Ernest Rutherford introduced to Robert J. Van de Graaff the urgent need to develop a better method of accelerating atomic particles to very high speeds.

During his investigation he comes across to the fact that atom smashing required very high energies. Natural radioactive elements such as the very expensive radium were sources of particles (alpha, electrons, as well as gamma rays) but their energy and their number were too low for penetrating the potential barrier of the nuclei of heavier elements. It was desirable not only such particles were available in adequate amounts and with sufficient energy to penetrate the atomic nucleus, but also that they be homogeneous and steady in energy and that they emerged from the apparatus in a parallel beam with little accompanying stray radiation.

By the 1920s the developments in nuclear physics emphasize the need of a new technique adapted to deliver enormous energies in concentrated form in order to penetrate or disrupt atomic nuclei. [5]

4. Invention and Evolution

The first working Van de Graaff generator produced 80 kV DC. A dual positive-negative Van de Graaff generator developing over 1 MEV was presented to the 1931 meeting of the American Physical Society [6].

Van de Graaff high voltage electrostatics generators were very simple using only 1 moving belt and 2 pulleys to produce high voltage direct current.

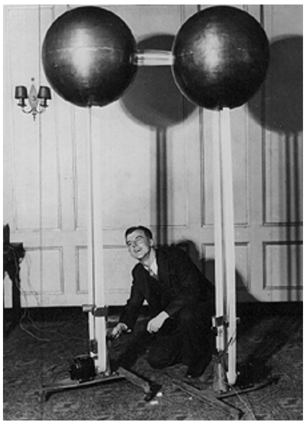

Figure 7. An early Van de Graaff generator being demonstrated by Robert J. Van de Graaff. [7]

In 1931 Van de Graaff began to construct a large double generator in an unused dirigible shed at Round Hill (South Dartmouth, Mass.) [3]

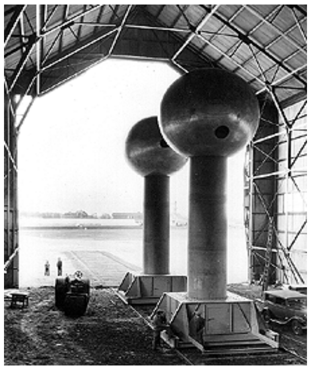

Figure 8. The Van de Graaff generator in the Hangar.

It consisted of two 7 m high insulating columns each containing two belts and supporting an aluminium sphere, 2 m in diameter. [3]

A laboratory was set up in each of the two domes. Here, scientists could study the effect in the accelerating tube that ran between the domes.

The columns were mounted on railway trucks so that the distance between them could be easily modified and also be wheeled out of and within the hangar. [7]

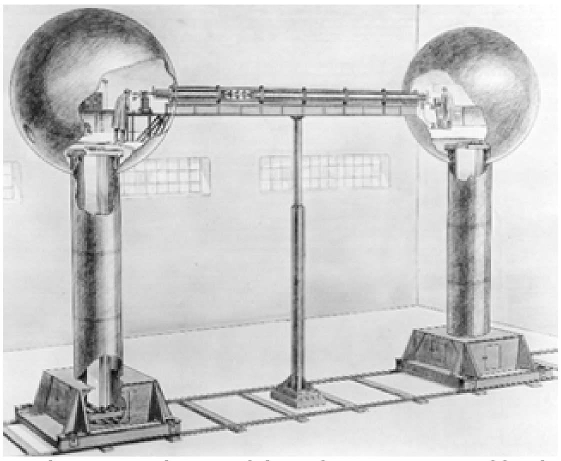

Figure 9. An image of the columns connected by the accelerating tube. [8]

It was functional in November 1933 and it was claimed to produce 7 million volts but in fact it developed about 5 Mev. [3]

Due to the difficulties of mounting the discharge tube between the spherical terminals this generator was never satisfactory as an accelerator. It was subsequently moved to MIT, where it was completely modified and used for atom smashing and high-energy X-rays research.

At MIT the Van de Graaff high voltage generator was enclosed in a pressurized tank filled with a blend of insulating gases which enabled the Van de Graaff generator to achieve even higher accelerating potentials. [6]

Finally in the 1950s was donated to the Boston Museum of Science and in 1980, was installed in the Thomson Theatre of Electricity of the museum. [3]

The two Van de Graaff high voltage generator terminals, were grafted together to form a singular huge terminal. The right column contained the working belts, motors, and brushes. The left column (which is now empty serves only as a support for the sphere) contained equipment to generate high energy x-rays. [8]

The electrostatic generator was likewise employed with advantage in non-nuclear applications.

5. How it works

5.1. Theory

To understand the bases of a Van de Graaff generator it is important to understand static electricity.

Static electricity is an imbalance in the amounts of positive and negative charges in the surface of an object.

Some atoms hold on to their electrons more tightly than others do. How strongly matter holds on to its electrons determines its place in the tribo-electric series. A material is more positive in this series if is more apt to give up electrons and more negative if is more apt to capture electrons when in contact with other materials.

The following table shows the tribo-electric series for many materials:

- Human hands -Very positive
- Glass
- Human ha
- Silk
- Paper
- Steel - Neutral
- Wood
- Hard rubber
- Nickel, Copper
- Gold, Platinum
- Silicon
- Teflon - Very negative

The relative position of two substances in the triboelectric series tells how they will act when brought into contact. For example, glass rubbed by silk causes a charge separation because they are several positions apart in the table. The farther the separation, in the table, the greater the effect. [5]

The term "static" in this case is deceptive, because it implies "no motion," when in reality it is very common and necessary for charge imbalances to flow.

Another important factor in electrostatics is humidity. If it is very humid, the charge imbalance will not remain for a useful amount of time. Humidity is the measure of moisture in the air. If the humidity is high, the moisture coats the surface of the material, providing a low-resistance path for electron flow. This path allows the charges to "recombine" and thus neutralize the charge imbalance. Likewise, if it is very dry, a charge can build up to extraordinary levels, up to tens of thousands of volts! [9]

5.2. Scheme of a Van de Graaff Generator

The generator consists of a well-rounded high-voltage terminal supported from ground on an insulating column, and of a charge-conveying system consisting of one belt of insulating material running in two rollers between this terminal and ground. [5]

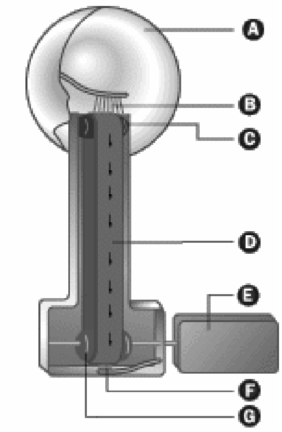

Figure 10. Scheme of a Van de Graaff Generator.

Legend:
A – Output terminal (collector)
B – Upper brush
C – Upper roller
D – Belt
E – Motor
F – Lower Brush
G – Lower roller

When the motor is turned on, the lower roller begins turning the belt. Since the belt is made of rubber, the lower roller begins to build a negative charge and by induction the belt builds a positive charge on the outside surface. This charge imbalance occurs due to the triboelectric effect: the lower roller is capturing electrons from the belt as it passes over the roller.

A conducting brush at the top of a belt is connected to the "collector". By this comb the positive charge of the belt goes to the collector while the rubber is moving. At the base of the roller is a comb which drains the negative charges on the outside of the belt to ground.

At any instant the terminal potential is $V = Q/C$, where Q is the stored charge and C the capacitance of the terminal to ground. [5]

Due to the geometry of the outer sphere the free charge will be uniformly distributed about its surface. As the generator continues to charge, a potential difference between the sphere and the grounded base of the Van de Graaff can reach nearly one-half of a million volts. In fact, the sphere will continue to build up charge until a voltage break down occurs in the air. Prior to the breakdown, the air around the sphere becomes ionized. The air turns from an insulator to a conductor. With the air ionized the electrons leap off the collector creating a brilliant spark.[1]

5.3. This Van de Graaff generator

This generator was constructed with materials that can easily be achieved.

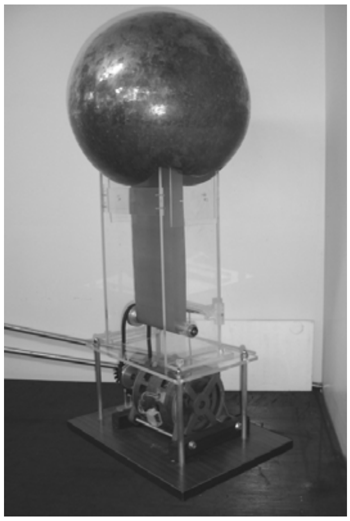

Figure 10. Picture of the Van de Graaff generator.

This is a basic Van de Graaff generator; build with two rollers, a belt, a motor, two combs and a collector (a sphere).

The spherical dome was build in copper by a copper artisan while the rest of the structure was home made. The generator has a column build with acrylic which supports a sphere of copper. The rollers of acrylic make a natural rubber belt turn vertically by action of an electrical motor. Near each roller is a comb made of copper wires. The upper comb collects the positive charges from the belt to the sphere will the lower comb drains the negative charges from the belt to the ground.

5.4. Safety

When using this device there are several safety measures that have to be taken in account.

If using a Van de Graaff generator in a classroom, do not allow students to use it unsupervised.

People with cardiac pacemakers should never operate the generator or come in contact with it.

Stay about 90 cm away from the collector while it is charged. Full intensity, white-hot sparks can jump as far as 38 cm, less intense, red-purple sparks can jump 50-76 cm. The current is too low to injure, a surprise spark is no fun. Keep the generator at a safe distance from the outlet where it will be plug in. If you're too close, you won't be able to turn it off safely.

Always discharge the collector dome between experiments using the discharge wand. Hold the discharge wand by the handle. Do not touch the grounding strap when discharging the generator. The voltage is so high that the current can pass through the insulation into the hand.

Do not run the generator continuously for long periods of time. Turn it off when not in use.

Keep the entire device clean and dry. Dust and moisture degrade the generator's performance. [10]

6. Hints

When trying to build an electrostatic machine there are some hints that can be very useful when the generator is not working as it should be.

Avoid using wood, cloth, paper or other fibrous materials as insulating structures. Their insulating properties will vary unexpectedly because of humidity changes, so on some days they are insulate and in others become conductive. Work with plastics and rubber.

Do not use sharp edged conductors or there will appear corona discharges in those edges. The charge will not build up on the sphere, instead it will leak into the air.

Keep the metal parts far away from each other and away from the “ground”. If oppositely charged parts are close together, or if charged parts are closed to grounded parts, they form a capacitor with significant value. This can slow the charged-up time of the device and make the electric field between them become extremely intense. This can cause sparks or silent and invisible corona discharges to appear on the metal surfaces. For any particular current, the lower the capacitance, the faster the device charges to maximum. The bigger the metal parts, the farther away they should be from each other.

Keep all insulating parts clean, because with dirt or dust they can become slightly conductive, especially when humidity is high.

To “see” the voltage, cut some short strips of tissue, and then stick them to the metal parts of the device with a bit of tape, so that the strips hang down along the metal. When the metal becomes charged, the tissue strips will be repelled outwards. The further they raise, the higher the voltage on the metal object. Motion of the tissue makes the voltage “visible”.

To keep the belt from wandering on the rollers, it is necessary to adjust the rollers so they are nearly parallel and the belt only drifts sideway very slowly. The slow drift can be stopped putting a lump in the center of the flat roller, for example, winding it with many turns of electrical tape. [11]

7. Demonstrations

Here are some of the most interesting demonstrations that can be done with a Van de Graaff generator. These demos allow people to understand electric fields and electric forces.

Sparks - When the grounded discharge wand is brought near the collector dome, lightning discharges will occur, accompanied by a crackling sound. Try varying the distance between the wand and the collector to see the different types of sparks the generator can produce. I believe the rule is 8 cm for every 100,000 volts.

Understand lightning and Tornadoes - In the darkness, place the fluoro-tube length ways above the VG and watch micro vortices (tornadoes) of plasma dance up and down the VG sphere and the tube. Watch as the top vortex on the fluoro-tube corresponds to the bottom vortex on the sphere. Watch as these vortices meet in mid air, a spark will jump to exchange a charge the way lighting does.

Paperclip Ray – Tape a short piece of wire or an unbent paperclip to the side of the generator sphere. Bend the wire so it points outwards. When the generator is running, a stream of charged wind spews forth. This stream is a genuine *Ion Beam*. It will electrify distant surfaces, charge whole people if they are standing upon an insulator, and will run e-motors and fluorescent tubes at a distance. Warning: never direct the ion beam towards a computer, it can induce electrostatic discharges inside the computer.

Hair Raising - Pick a volunteer preferably with long blonde hair. Darker hair is too heavy and short hair isn't very dramatic. The volunteer should also have clean, unprocessed, un-moussed hair. Thoroughly discharge the generator before beginning. Have the volunteer stand on an insulating spot and place one hand on the generator. The volunteer should not be touching the table or anything else and also not be wearing a jacket, hat, or layers of loose clothing. These can serve a discharge points. Turn the generator on and wait. The volunteer's hair will begin to levitate by electrostatic repulsion. When you are done turn off the generator. Tell the volunteer to remove her hand. Discharge the generator with the discharge wand. Tell your volunteer to "shake off" the excess charges before leaving the insulating spot. This will reduce or eliminate the shock.

Demos on electrical repulsion:

Lay a stack of pie plates on the generator and turn it on. The plates will rise off one at a time by electrostatic repulsion as if they were UFOs.

Blow soap bubbles at the generator sphere. They will be initially attracted, but then will become charged by ion wind and will be violently repelled. They will also be attracted to any other object.

Tear long narrow strips of newspaper and tape them on to the collector with scotch tape. Turn on the generator. The strips will try to align themselves with the electrostatic field.

Bring a lit candle near the collector after the generator is turned on. The flame will deflect away from the collector. This shows the flow of ions away from the collector and mimics the solar wind to a certain extent. If you bring the flame very close, a portion of the flame will be attracted toward the collector. The ions in the flame are separating by charge. [10/11]

8. Conclusions

The Van de Graaff generator in its simplest form is seen as a didactical instrument, because of its solidity and simple construction. This generator became an ideal demonstration apparatus of electrostatic influence machine.

Van de Graaff high voltage electrostatic generators are used in public schools and universities for teaching basic principles of high voltage electrostatics charge and laws of electrostatics. The Van de Graaff generator is extremely useful because it produces electric fields which are strong enough to be measured, manipulated, felt directly and played with.

Men have always been fascinated by lightning and big sparks, therefore this machine was always the ideal and much appreciated display in important exhibitions, science museums and science centers. Table top Van de Graaff generators develop over 200,000 Volts and floor models offer up to 1,000,000 Volts of high voltage lightning electrical discharges.

9. Acknowledgements

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