Misbehaving Electrostatics II

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The school Van de Graaff generator is one of the basic school instruments used for electrostatics experiments. Nevertheless, the principle of its function is often a little bit of a mystery to many people. How does it really work? How to look for the fault when it doesn’t work properly? An unusual way of looking for the answers to these questions with the use of a digital oscilloscope with a high-voltage probe is the content of this paper.

Introduction*

To find out if (and how) a body is charged, we usually use an electroscope or some electronic instrument or indicator of electric charge. Charged bodies also attract uncharged pieces of paper, hair or other small objects (e.g. due to their polarization and subsequent attraction in an inhomogeneous field of the charged body).

The operation principle of an electroscope (electrometer) lies in mutual repulsion of parts with the same electric charge. Electronic charge indicators use a measuring capacitor (with a significantly larger capacity than the examined metal body) with one grounded electrode. After connecting the second pole of the capacitor to the body, the capacitor is charged with the same electric charge as the body. The charge can then be determined from the voltage on the capacitor and its capacity. This principle is described in detail in [2].

If we conductively connect the charged body with the ground, we dissipate its charge (only a part of its charge in the case of a body made of insulator) into the ground. During this connection, electric current flows for a while. The size and duration of this “current pulse” depends on the capacity of the body (size, shape, etc.) and on the overall resistance of the connection with ground. In the following text, the connection with ground will be represented by a high-voltage (hereinafter referred to as “HV”) oscilloscope probe.

Oscilloscope and High Voltage Probe

We usually use an oscilloscope to display the time dependency of electrical quantities in low-current circuits. Joined with a high voltage probe, however, it may be a useful tool for electrostatics. A digital oscilloscope (nowadays easily available) is suitable for this use, enabling capturing, displaying and measuring

* Adapted and modified from [1].

of one-time events (peaks, individual pulses). The description of how to operate an oscilloscope is not the subject of this article, basic information can be found, for example, in [3].

Standard voltage ranges of the oscilloscope can be increased by using a suitable probe (which combined with the oscilloscope input represents a frequency-independent voltage divider). In our experiments, we used a high-voltage probe 1000x allowing a safe voltage measurement at the tip of up to 40 kV. From the point of view of the body to which the probe is approached, the probe with the oscilloscope can be replaced by a parallel combination of a resistor with a resistance of 100 MΩ and a capacitor with a capacity of about 3 pF connected to ground.

Fig. 1 Oscilloscope and high voltage probe

The output information is potential (voltage to ground) curve of the probe tip or rather the time potential curve of the body to which the probe is connected.

What will we need?

For the following experiments, we will need an oscilloscope with a high voltage probe and: PVC rod (waste pipe or vacuum cleaner tube), glass rod, flannel cloth, artificial deerskin and a piece of skin to rub the rods with, laboratory stand with clamp to attach the high voltage probe, screwdriver and school Van de Graaff generator .

Fig. 2 Equipment for experiments

For our experiments, we used a school Van de Graaff generator NTL DE525-1B with a belt drive. The lower pulley (cylinder) is aluminium, the upper one is made of plexiglass and the belt is made of silicone rubber.

Discharge of a charged PVC rod

In [1], we explored the discharge of an electrically charged rod into a range of metallic objects of differing sizes. These included the sharp tip of a probe, a ball mounted on the tip of the probe, and two larger balls attached to the oscilloscope probe. Our investigation focused on the impact of the size of the metallic object, as quantified by its capacitance, on the magnitude and duration of the voltage pulse recorded by the oscilloscope.

For the purposes of further examination, let us first summarize two key experiments from this article.

First, we gradually moved the charged PVC rod closer to the sharp tip of the HV probe. As it gradually approached, we observed a number of pulses on the oscilloscope screen at a distance of a few centimeters from the tip of the probe – the rod discharged into the tip. The impulses had a negative polarity, a negative charge burst from the rod. We confirmed the known saying that a PVC rod rubbed with flannel or synthetic buckskin is charged negatively.

When the rod was moved along its axis at a constant distance from the probe, another charge was emitted to the tip of the probe (we see another series of impulses on the oscilloscope screen). Therefore, only a part of the charge from a small area of the charged rod from the insulator is emitted to the tip of the probe. This fact allows for further detailed examination of charged bodies from insulators, such as the belt or pulleys of a school Van de Graaff generator.

We repeated the experiment with a glass rod charged by rubbing it with a piece of leather.

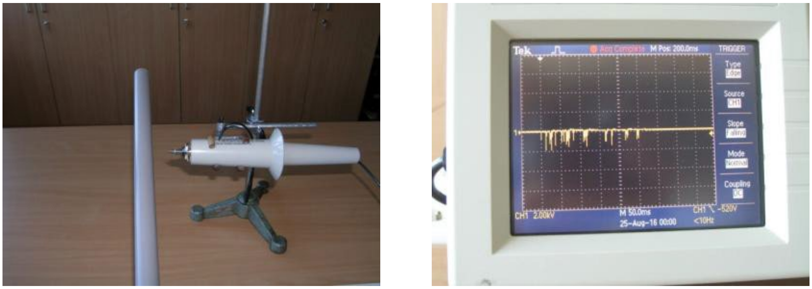

Fig. 3 Discharge of charge from a charged PVC rod to the tip of the probe

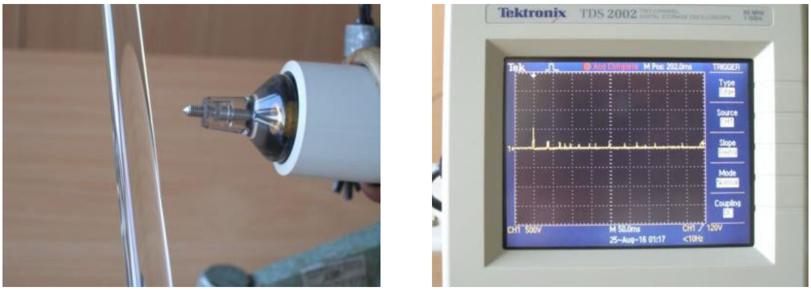

Fig. 4 Discharge of charge from a charged glass rod to the tip of the probe

Similarly to the case of the PVC rod, we also observed a series of impulses on the oscilloscope screen when gradually approaching the glass rod to the tip of the probe. However, the impulses had a positive polarity, a positive charge was emanating from the rod, and the glass rod is charged positively when rubbed with leather.

An important fact was that, in both the glass and PVC rods (regardless of the sign of the charge on the rod), the experiment proceeded similarly in the case of discharge of charge to the sharp tip and in the case of transfer of charge to the curved surface. When the charged rod is brought close to the sharp tip of the probe, a strong electric field is created in which the surrounding air is ionized, charged particles (carriers of charge of both signs – ions and electrons) are created, and a "conductive channel" between the rod and the tip is formed.

In the case of "smooth surfaces" of the rod and ball (mounted on the tip of the probe), a sufficient strong electric field is created between them only when they are brought much closer together. The amount of charge transferred at once by the resulting electric discharge is then larger.

How does a school Van de Graaff generator work?

A school Van de Graaff generator is a basic tool for experiments in electrostatics. Nevertheless, the principle of its operation is often shrouded in mystery for many people. Most sources of information (internet, but also textbooks) only describe the arrangement of the Van de Graaff generator (pulleys, belt, drive, brushes - combs, spherical conductor). Only a few of them [4], [5] for example, deal in detail with the principle of operation of the generator and describe the charging processes taking place on its individual components. In addition, there are various types of school generators that differ in the materials used for the pulleys and belt, the location of the electrodes, or the method of drive.

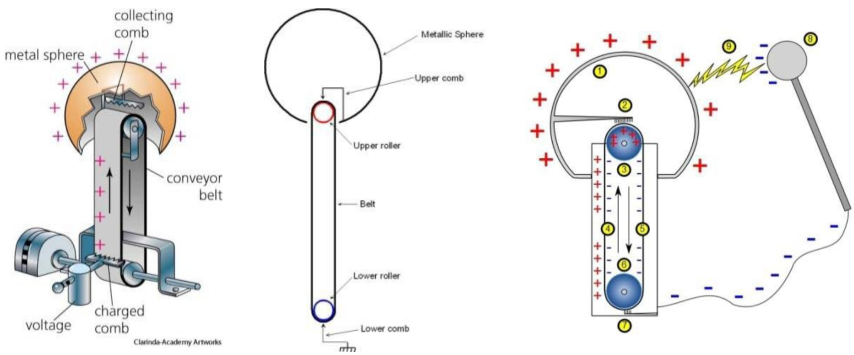

Fig. 5 Images obtained from an internet search engine to explain the operation of a Van de Graaff generator

It is usually easy to explain that the charge brought inside the spherical conductor (hollow metal ball) from the top collecting brush is distributed over the outer surface of the ball due to mutual repulsion of charges of the same sign. But what determines the "willingness" of the belt to accept the charge from the bottom brush and the "willingness" to transfer it to the top part through the collecting brush to the spherical conductor? What determines the sign of the charge that the conductor is charged with?

Let's try to find an answer to these questions using the following experiment. Remove the spherical conductor from the school Van de Graaff generator, unscrew the bottom brushes and the top collecting brush with the holder. Remove all charged bodies from the vicinity of the device. Also remove the residual charge from both sides of the belt using a grounded conductor (or just leave the device standing for a few minutes).


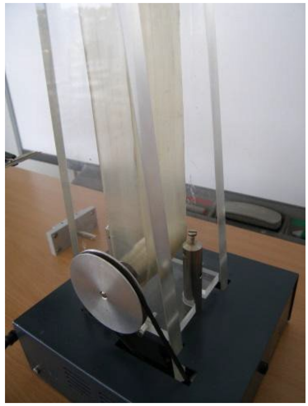

Fig. 6 School Van de Graaff generator without the collecting brushes

We bring the tip of the probe (near the location where the bottom brush is in the assembled state) close to the bottom of the belt. We can also attach a crocodile clip to the tip of the probe, secure the detached bottom brush in it, and bring it close to the bottom of the belt.

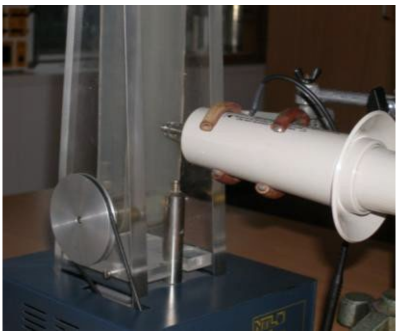
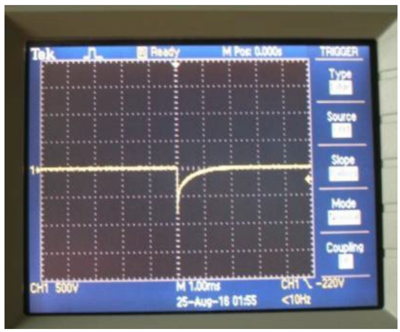

Fig. 7 Examining the charge on the belt in the area between the pulleys.

After turning on the belt of the Van de Graaff generator, we observe negative pulses on the oscilloscope screen, similar to what happened when a negatively charged PVC rod was brought close to the probe tip (see Figure 3 on the right and Figure 7 on the right, in Figure 7 there is only higher temporal resolution). It is noteworthy that the frequency of these pulses significantly decreases after a short time (about 10 to 20 seconds from starting the belt movement). We have therefore found that the belt itself is overall negatively charged at the point of proximity to the probe in our device. When the grounded probe tip or grounded brush is brought close, this charge causes positive charge to spark (discharge) on the belt. The same result is obtained when measuring in both directions of belt movement (up and down).

After performing the previous measurement, now move the probe tip to the top of the belt so that it is "pointing" at the top pulley. The measurement can be taken with the metal holder with the top brush removed, or it can be left in place, or the probe tip can be touched directly to the holder.

The oscilloscope now registers positive pulses – the belt and the top pulley together appear to be a positively charged system, causing positive charge to spark on the (grounded) probe.

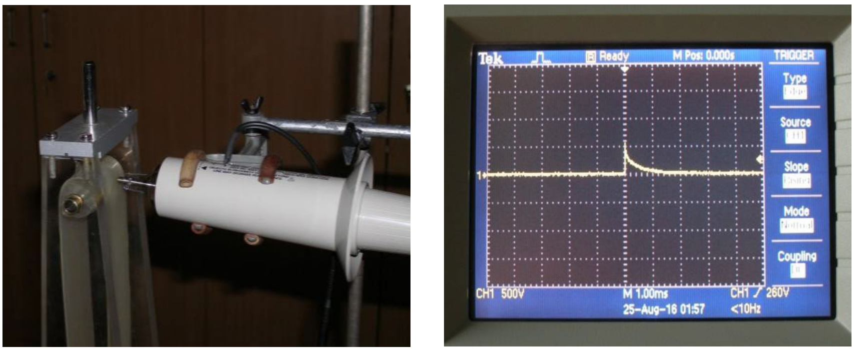

Fig. 8 Examination of the overall charge of the belt and top pulley system

The pulse rate of the recorded pulses then decreases after a short time from starting the belt movement, similar to what was observed in the measurement in the lower part of the belt.

What caused the belt to charge negatively simply by being turned on, without the presence of brushes? The answer is indicated by a mere look at both pulleys of our Van de Graaff generator. They are made of different materials. The lower one is aluminium, the upper one is made of transparent plexiglass.

Contact between the belt and the aluminium pulley

Now let's consider for a moment that the belt is only winding around a single, aluminium pulley. As the belt winds around it, the pulley becomes positively charged due to the so-called triboelectric effect, and the inner part of the belt becomes negatively charged, similar to how a PVC rod becomes negatively charged and a flannel cloth or artificial fur becomes positively charged when they are rubbed together (in mutual contact). The signs of the charges correspond to the placement of silicone rubber (-) and aluminium (+) in the so-called triboelectric series. The effect is significant, as these materials are far apart in opposite parts of the series. Thanks to the conductivity of the aluminium pulley, the resulting positive charge can move over its entire surface. The specific distribution of charge on the pulley also depends on the charging state of the belt due to electrostatic induction.

In the case of our Van de Graaff generator, the lower aluminium pulley rotates on bearings mounted in an insulating structure - it is not connected to ground. When the probe tip is brought close to the metal shaft of the pulley, we observe positive polarity pulses on the oscilloscope screen. The aluminium pulley therefore does indeed charge positively as the belt winds off of silicone rubber.

Contact between the belt and the plexiglass pulley

Now let's imagine that the belt is only winding around a plexiglass pulley. Similar to the case of aluminium, plexiglass (polymethylmethacrylate) (0–) becomes positively charged in contact with silicone rubber (–). However, the effect is weaker than in the previous case, as plexiglass and silicone rubber are closer to each other in the triboelectric series. The overall positive charge on the surface of the plexiglass pulley will be smaller than that on the aluminum pulley, but plexiglass is an insulator – the positive charge will remain on the surface of the pulley where it was "generated".

The Van de Graaffův generator as a charge pump

Now let's "put together" both pulleys, with the aluminum one at the bottom and the plexiglass one at the top (the arrangement of our device). As a result of the processes described above, the inner part of the belt will charge negatively, while the pulleys will charge positively.

If we therefore bring a grounded electrode (probe tip, grounded brush) from the outside towards the space between the pulleys, an electric field will be created between it and the charged belt. Due to the strong electric field in the vicinity of the brush tips or probe tip, air ionization occurs, a "conductive channel" is created, and positive charge is transferred to the outer surface of the belt. That is why we observed negative pulses on the oscilloscope screen in Fig. 7 – an electric current flowed from the probe to the belt. The belt (which is itself made of an insulator) is therefore negatively charged on the inside and gradually charges positively on the outside.

If we do not remove charge from the outer side of the belt (we have the upper brush removed or just the conductor removed), the positive charge on the outer side of the belt will gradually balance out the negative charge on the inner side – from the perspective of the bottom, grounded electrode, the belt will no longer "appear" electrically charged, the electric field between it and the electrode will decrease, and further emission of positive charge to the belt will stop. This explains the observed (see above) decrease in the frequency of pulses recorded by the oscilloscope after a certain period of time from the start of belt movement.

Let's now take a look at the situation with the upper pulley made of plexiglass. As previously mentioned, when the belt is moving, this pulley becomes positively charged, while the inner surface of the belt becomes negatively charged. In the part where the belt is wrapped around the pulley, the negative charge on the inner surface of the belt is compensated by a positive charge on the surface of the pulley. The system of the upper pulley along with the belt therefore appears neutral or slightly negatively charged (taking into account the charging of the belt and the lower, aluminium pulley) to its surroundings. However, if positive charges accumulate on the outer surface of the belt due to the negatively charged inner surface of the belt in the space between the pulleys, the belt as a whole (both surfaces) along with the upper pulley will become positively charged. Therefore, if we approach the upper pulley with a grounded probe of an oscilloscope or a collecting brush located in the cavity of a spherical conductor, the positive charge of the system of the pulley and belt will be emitted from the belt due to its positive charge.

In order for a positive charge to "ascend" to the upper collecting brush from the upper pulley, it must "board" the belt in the lower part of the device. In the case of our second measurement with the probe tip at the upper pulley (Figure 8), a positive charge that had previously "boarded" the belt from the probe tip during the first measurement with the probe tip between the pulleys (Figure 7) "ascended" into the collecting brush. Therefore, the oscilloscope only registered positive pulses for a limited period of time after the belt movement was initiated when the bottom brushes were removed. When one or both of the bottom (grounded) brushes are subsequently added (simply by holding them near the place where they belong with your hand), the oscilloscope registers positive pulses continuously.

Note: The situation with the lower conductive aluminium pulley is somewhat different from that of the upper insulating pulley. As mentioned, the charge distribution on its surface is influenced by the charge on both sides of the belt due to electrostatic induction. If the belt is overall less negatively charged (a positive charge has "boarded" the outer surface of the belt), there is also less positive charge on the surface of the pulley itself in the area of contact between the belt and pulley.

Conclusion

A digital oscilloscope with a high voltage probe is a useful tool for understanding the laws of electrostatics. It allows for the examination of the "time course" of various charging processes and allows for a detailed local examination of the charge on the surface of insulating surfaces (such as charged rods or the belt of a school Van de Graaff generator).

The operation of many school Van de Graaff generators is based on the triboelectric effect - charging bodies made of different materials through their mutual contact. The state (and cleanliness) of the surface of the belt and the pulleys is therefore important for the proper functioning of these devices. Ensuring sufficient mutual contact between these components through proper tensioning of the belt is also important. Metal collecting brushes must not touch the belt, as this will cause mechanical damage to its surface. For proper operation of generators (with one conductor), the lower brush must be grounded. In the case of belt-driven generators powered from the electrical grid, this grounding is usually done through a protective pin of the electrical outlet.

Acknowledgement

I would like to thank Professor Jaroslav Krejčí of Gymnázium Na Pražačce for inspiration and pointing out inconsistencies in textbooks and other study materials on basic experiments in electrostatics. The related discussion was the initial impetus for the creation of this article.

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