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EXPERIMENTS WITH A TETHERED DRONE TO INVESTIGATE INDUCED CHARGES ON A VERTICALLY ARRANGED CONDUCTOR DURING FAIR WEATHER

Marcelo Arcanjo Pol Fontanes Michele Urbani Joan Montanyà
Lightning Research Group. Universitat Politècnica de Catalunya - BarcelonaTech (UPC), Terrassa, Spain.

Abstract – To better understand the phenomena associated with electrostatic charges and potential distribution over vertical conductors, this work describes preliminary results obtained with a tethered drone that is used to lay vertically a 100-m long-stranded copper wire. Several flights were conducted in fair weather conditions. In the first configuration, a conductive spherical shell with a spool for the wire is placed in a Teflon holder and used for ensuring that the charges inducted on the conductive body do not produce any corona from the bottom of the system. A field mill is placed below the sphere at a fixed distance, and its measurement can be used as a reference to the charge distribution over the sphere during the flights. The second configuration consists of grounding the bottom sphere, taking the null potential up to the tip of the wire that is deployed. In this setup, several approaches for measuring currents were explored.

1 - INTRODUCTION

The background electric field can reach a few hundred volts per meter on the earth's surface during fair weather conditions. Tall and elevated structures effectively distort their surrounding electric field and can, eventually, accumulate surface charges. Modern wind turbine blades, as an example, can get charged, reach a potential of several kilovolts, and cause electrostatic discharges (ESD) that stress the wind turbine's rotor bearings and other parts of its mechanical systems.

On the investigation of induced currents in stormy weather, Davis and Standring [1] conducted in 1947 an experiment with tethered balloons, reporting currents in the range of milliamperes to the kiloamperes (when the balloon was effectively struck by lightning). The measurement of the electric potential at different altitudes using a wire tethered balloon was performed by Vonnegut et al. [2]. At altitudes of 1000 m, they reported values close to 100kV. Holzworth [3] used a high impedance device for measuring the potential and reported values of 150kV at altitudes near 600 m. In addition to effects caused by potential differences, the mechanical movement of wind turbines can avoid the shielding effect caused by space charges. Observations made by Montanyà et al. [4] support the hypothesis that the blade rotation contributes to the existence of stronger local electric fields at the blade's tip. These observations are aligned with previous works [5-7] that relate the wind turbine blade rotation to an increase in its susceptibility to receive lightning strikes.

López et al. and Montanyà et al. measured induced voltages and currents in conductive tethered kites [8] and drones [9], respectively. The deployment of a vertical conductive wire causes a current flow due to induced charges. The high potential difference between the grounded cable and the local potential at certain altitudes may also lead to corona point discharges. Recently, Hong et al. [10] indicated evidence of corona discharges observed in fair weather in an experiment with a tethered grounded balloon and a sharp tip. Currents in the order of a few hundreds of nanoamps were obtained when the balloon exceeded heights of about 65 meters. They estimated the potential difference for the environment and calculated an average electric field at the ground level of 115 V/m.

In this work, we discuss preliminary results obtained for flights with a tethered drone to investigate charges induced in a system composed of an insulated sphere and a vertical wire. In a secondary approach, the system is grounded, and we observe possible indications of corona discharges. This study reveals important contributions to the understanding of corona discharges from grounded and floating conductors, that may be associated with upward leaders' formation from different structures.

2 – EXPERIMENTS IN THE LABORATORY

We performed experiments in the laboratory aiming to represent the situation when the system is composed of the sphere connected to the vertical wire and insulated from the ground. For that, we used a small electric field mill near the sphere. Its output voltage could give an indication of the distribution of charges over the sphere.

2.1 – CHARGING A FLOATING SPHERE WITH CORONA DISCHARGES

With this experiment, we propose to charge the sphere by producing corona discharges in the tip of a wire connected to it. Figure 1 shows the setup used for this investigation. A spherical shell with a diameter of 30 cm is placed between two plates with 2 m of diameter, electrically floating and supported on a Teflon structure. On the top of the sphere, a straight insulated wire is connected with its tip exposed. The gap distance between the tip of the wire and the upper plate is about 4 cm.

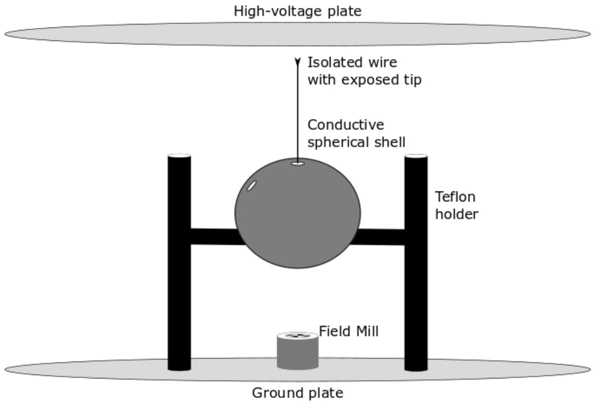

Figure 1 - Insulated sphere-wire subject to high electric field.

The measurements of the Field Mill (FM) provide a qualitative idea of the charge distribution in the setup. The experiment performed consists of increasing the upper plate voltage from zero to a high-voltage level (6 kV, 9 kV, 12 kV, or 15 kV), with a slope of 10kV/s. For three seconds, the voltage remains constant and returns to zero, with the same rate of change.

The output of the Field Mill indicates the electric field due to the upper voltage applied. We are interested in the values obtained when the upper plate voltage returns to zero. This indication should be zero if the sphere-wire returns to the initial conditions.

Figure 2 shows the data obtained during the experiment, when positive (a) and negative (b) voltage were applied. For the positive voltage, we observed that when 6 kV or 9 kV were applied, the sphere did not get electrically charged, and the Field Mill readings were the same as at the beginning of the experiment. However, when 12 kV or 15 kV were applied, the sphere gets charged.

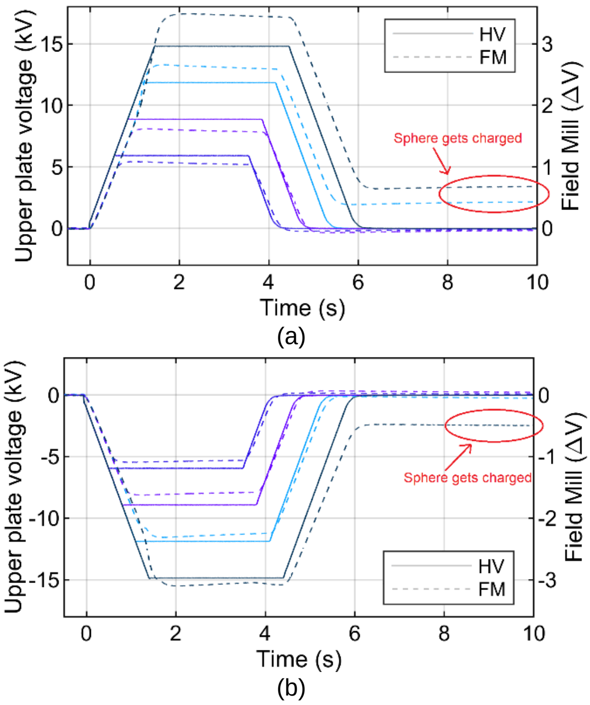

Figure 2 – Charging the sphere with positive (a) and negative (b) net charges by producing corona at the tip of the wire.

We were able to prove this condition by discharging the sphere with a grounded cable and using a camera with an enhancement for the ultraviolet, which let us able to see tiny corona discharges from the tip of the wire. When negative voltage is applied, only in the condition of -15 kV we could charge the sphere.

When the upper plate voltage increases positively, the charges in the wire-sphere system are rearranged (polarized). Negative charges are concentrated on the tip of the wire, and positive on the bottom of the sphere. That explains the reading of positive values on the Field Mill. If the enhancement of the local electric field at the tip of the wire is high enough (for this setup, when the voltage is about 11 kV), negative corona discharges occur, and the sphere gets charged positively.

The opposite happens when the voltage applied is negative. Positive corona is observed only for higher magnitudes if compared with negative (Figure 2b). For this setup, we observed a threshold voltage of about -13.5 kV. In this work, we did not measure the net charge of the sphere after the experiments.

3 – EXPERIMENTS IN THE FIELD

For the experiments in the field, a multicopter drone is used to deploy and keep a vertically stable conductive wire, as shown schematically in Figure 3. A conductive spherical shell with a spool for the wire is used for making sure that the separation of charges in the conductive body does not produce any corona from the bottom of the system. The Field Mill is placed below the sphere at a fixed distance, and its measurement can be used as a reference of the charge distribution over the sphere during the flights. A current sensor is positioned on the top of the sphere to detect corona pulses.

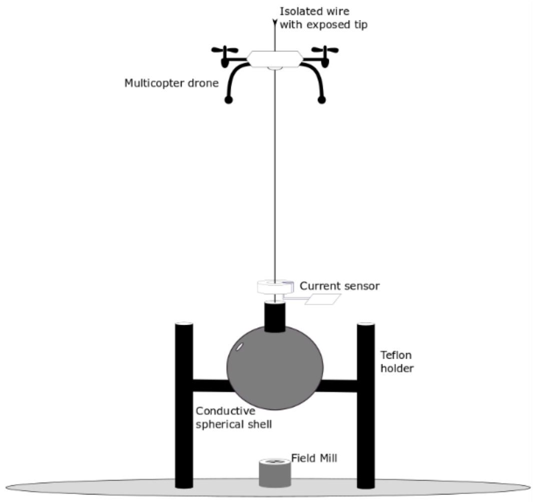

Figure 3 – Floating sphere with vertical wire connected.

Figure 4 shows a picture of the site where the flight reported in section 3.1 took place (on 11th Nov 2019). The sky was very clear with no clouds nearby. The experiment was performed in the morning to avoid windy conditions.

Figure 4 – Picture of the site where flight 1 took place.

As discussed in [9], the potential ϕ of a vertical perfect conductive wire is the average potential of the atmosphere $\phi(z)$. In fair weather, the average potential gradient is about 100 V/m [11]. Thus, a 100-meter vertical wire will be subjected to a potential difference of about 10 kV and will develop an average potential of 5 kV. Negative charges will be attracted to the upper tip of the wire, and its bottom part will have positive charges.

Figure 5 shows schematically the potential of the induced charges on an electrically floating wire and its potential. We follow the idea proposed in [12], considering the wire a perfect conductor, negative and positive charges would be induced on it, and this potential, added to the background potential, corresponds to the average potential expected (in our case, 5 kV).

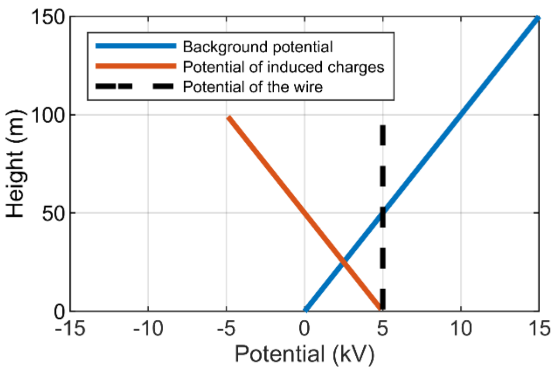

Figure 5 – Potential of a 100-m floating wire deployed vertically. The dashed line is the sum of the background potential and the potential of the induced charges.

3.1 – FLIGHT 1: INSULATED SPHERE WITH WIRE-DISRUPTION

With this experiment, we tried to detect corona pulses from the wire and measure the electric field from the bottom of the sphere to observe the distribution of charges on the sphere-wire system.

When the maximum altitude (110 meters for this case) was reached, the wire breaks at the point of connection with the sphere. Figure 6 shows the indications of the FM (measured in volts and not converted to electric field). During the fast-rising of the drone (from 0 to 55 seconds), the voltage increases, indicating that the bottom of the sphere is positively charged. When the wire breaks from the sphere, the FM indication suddenly drops.

Most of the charges of the system appear to be accumulated along the wire, since, when it breaks from the system, the level indicated by the field mill is not much higher than before the experiment. However, to verify if the sphere presented any remaining charge, the sphere is grounded at t = 180 seconds. One can note a small step in the FM signal at that moment, indicating that the sphere was positively charged. The results obtained with this experiment suggests that the separation of charges intensifies the higher the wire extends while being deployed vertically.

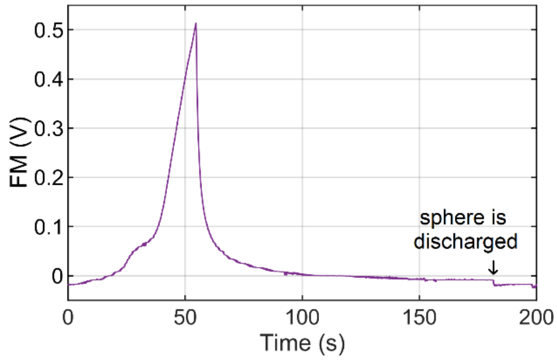

Figure 6 – Electric Field Mill uncalibrated measurement for Flight 1.

Figure 7 depicts the waveform of the discharge of the sphere using a 50-ohm shunt resistor, with a typical oscillating waveform. For this measurement, the peak current saturates the scale of the digitizer used when it reaches more than 20 milliamperes. The total duration of the discharge is less than 800 nanoseconds, and the charge transferred (calculated with the saturated signal) was 160 pC. This value is much lower than the one reported in [9], indicating that most of the charges were distributed along the wire.

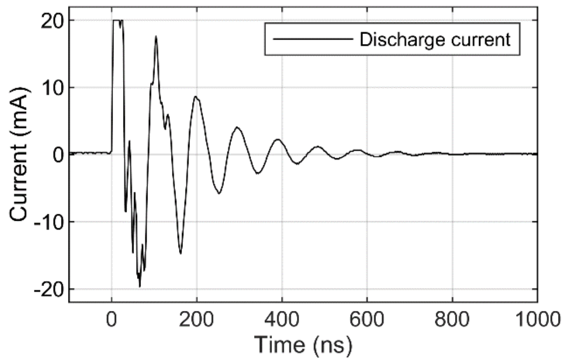

Figure 7 – Discharge current of the charged sphere.

3.2 – FLIGHT 2: INSULATED SPHERE WITH VERTICAL WIRE

Flight two was performed on 21st Feb 2020. For this test, the drone rose with a lower speed than in the case reported in flight 1. Figure 8 shows the measurement of the Field Mill and the simultaneous altitude of the drone.

The wire does not touch the ground at any moment of this experiment, and during the descent of the drone, the wire is collected by a motor installed inside the spherical shell.

From 0 to 100 seconds the drone rises to an altitude of 115 m. Similar to Figure 6, the voltage indicated by the Field Mill also increases due to the polarization of charges. After 100 seconds, the drone starts to descend, and the wire is spooled back inside the sphere. At 400 seconds, the drone is back to the initial position, and one can see that the potential measured by the Field Mill is negative and slowly returns towards zero.

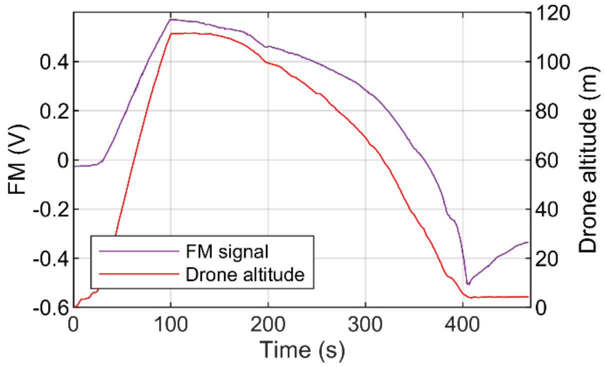

Figure 8 – Drone altitude and FM signal.

From these results, it is evident that some mechanism charged the sphere-wire system. However, the polarity obtained after the drone descends was the opposite of what we obtained in the laboratory experiments (section 2.1). Therefore, the residual net charge of the sphere was negative, and it was not possible to ensure that corona discharges occurred and were responsible for charging the system.

3.3 – FLIGHT 3:
MEASURING CURRENTS WITH GROUNDED SPHERE

Figure 9 shows a picture of the site where the third flight was performed (on 19th Dec 2019). On this day, the weather was cloudy with some fog, but not thundery. In order to increase the probability of corona current, we grounded the sphere, in this way, the zero potential was taken to the tip of the wire. In this case, a supposed 100 V/m potential gradient would subject the wire to a potential difference of 10 kV. We used a low-sensitivity current ammeter that allows measurements of the average current from the picoamperes scale.

Figure 9 - Picture of the site where the flight reported in 3.3 took place.

The total time to reach 100 meters was 5 minutes (300 seconds), during this interval, the drone was kept steady several times to verify the behavior of the current. Figure 11a shows the measurements of current and the drone altitude, Figure 11b depicts the detail of the current correlated with the drone speed.

One can note from Figure 11a that the experiment starts at t = 0, and the drone rises to about 33 meters (at t = 110 seconds), for a few seconds, the drone is kept steady, and the current decreases. The current resumes increasing when the drone is pushed up, until 170 seconds, when it stops again. In Figure 11b, the drone speed presents a strong correlation with the current through the wire when the drone is rising. When the drone is steady, it is possible to see a steady "background" current in the range of a few nanoamps.

At t = 250 seconds, the drone rises from 60 meters to 100 meters, and when it reaches 80 meters, the current inverts its polarity and increases abruptly comparing with the previous values. The correlation observed with the drone speed no longer exists. When the drone is steady at 100 meters, the current is about -150 nanoamperes.

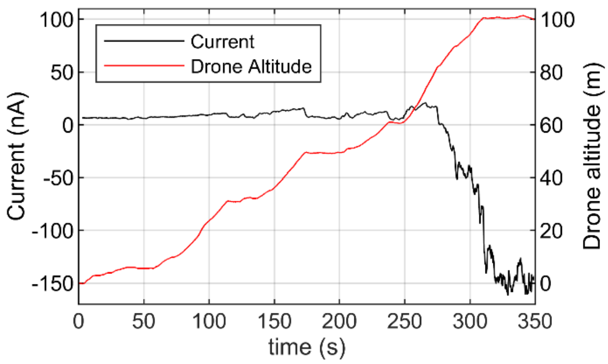

Figure 10a – Measured current compared with drone altitude.

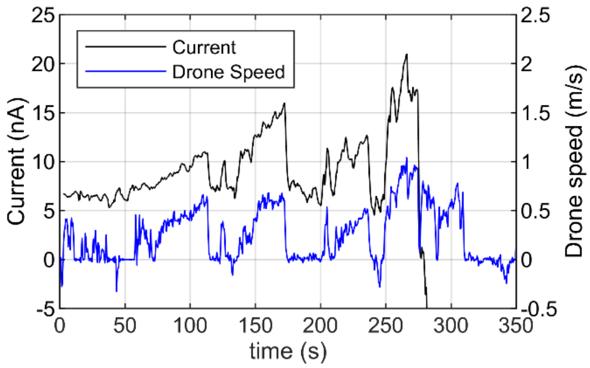

Figure 11b – Measured current compared with drone speed.

The indications of current shown in Figure 11a suggest that the potential difference that the tip of the wire was subjected was enough for producing corona. However, if one takes into consideration the curve shown in Figure 5, in which the upper potential is positive, no inversion in the polarity of the current would be expected. In this case, with misty weather, we should not expect a uniform electric field with a positive potential gradient.

4 - CONCLUSIONS

This paper shows preliminary results of flights with a tethered drone and a sphere configured insulated from the ground or grounded. In the laboratory, we performed experiments that show how the effects of charge induction happen with the sphere and how corona discharges can charge the insulated system when it is subjected to a very high potential difference.

In the field, three flights were performed in different configurations for observing qualitatively how the potential rises and the charge separation. In the first flight, we observed that most of the charges were concentrated in the wire, and the sphere presented some positive charge after the rupture of the wire. In the second flight, the drone altitude was acquired simultaneously with the readings of the electric Field Mill, and we observed that the system gets charged after collecting the wire. In the third flight, in a different weather condition, we show some possible evidence of corona current, obtained when the drone altitude is higher than 80 meters.

We believe that the current probe was not able to measure corona pulses due to the large distance to the tip of the wire (in flights 2 and 3), and for solving this issue, we are currently developing a sensor that will be attached to the tip of the wire.

The data presented are useful for understanding some conditions that tall and elevated structures, such as wind turbine blades and towers are subjected to. In future works, we intend to conduct more flights and quantitatively assess the data, discussing, with the aid of models, electric field behavior and thresholds for corona occurrence, as well as improve the methods for measuring corona burst pulses.

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Main author
Name: Marcelo Arcanjo
E-mail: marcelo.augusto.sousa@upc.edu