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Key Points:

- Periodic discharges are emitted by rotating wind turbines
- Rotating blades are less shielded by corona
- Rotation favors occurrence of discharges compared to stationary tall objects

Supporting Information:

- Readme
- Wind Turbine Upwards

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Lightning discharges produced by wind turbines

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Abstract New observations with a 3-D Lightning Mapping Array and high-speed video are presented and discussed. The first set of observations shows that under certain thunderstorm conditions, wind turbine blades can produce electric discharges at regular intervals of ~3 s in relation to its rotation, over periods of time that range from a few minutes up to hours. This periodic effect has not been observed in static towers indicating that the effect of rotation is playing a critical role. The repeated discharges can occur tens of kilometers away from electrically active thunderstorm areas and may or may not precede a fully developed upward lightning discharge from the turbine. Similar to rockets used for triggering lightning, the fast movement of the blade tip plays an important role on the initiation of the discharge. The movement of the rotor blades allows the tip to "runaway" from the generated corona charge. The second observation is an uncommon upward/downward flash triggered by a wind turbine. In that flash, a negative upward leader was initiated from a wind turbine without preceding lightning activity. The flash produced a negative cloud-to-ground stroke several kilometers from the initiation point. The third observation corresponds to a high-speed video record showing simultaneous upward positive leaders from a group of wind turbines triggered by a preceding intracloud flash. The fact that multiple leaders develop simultaneously indicates a poor shielding effect among them. All these observations provide some special features on the initiation of lightning by nonstatic and complex tall structures.

1. Introduction

Lightning is one of the major causes of severe damage to wind turbines and produces millions of U.S. dollars of losses per year (see *Braam et al*. [2002] for a cost analysis). About 15 years ago, a large wind farm in the North Sea near Helgoland (Germany) suffered such large losses because of lightning strikes that its operation was no longer cost effective [*Kithil*, 2011]. Multimegawatt wind turbines are tall structures with a higher probability of being struck by normal negative cloud-to-ground lightning than their surroundings [*Rachidi et al*., 2008]. In such flashes a negatively charged leader propagates down from the cloud and connects with an induced upward positive leader from the tall object in the final tens of meters, followed by one or more intense current pulses called return strokes [*Rakov and Uman*, 2007]. However, when towers and natural objects rising more than 100 m above their surroundings are exposed to strong local electric fields under thunderclouds, their propensity to initiate an upward propagating leader itself is increased [*Berger*, 1967]. The upward leader can trigger return strokes as it reaches the charge in the cloud above. Especially when the charge in the cloud is of positive polarity, the flow of intense current can last long (up to a few hundred milliseconds) and cause severe damage to wind turbines (see standard *International Electrotechnical Commission* (*IEC*) *61400–24* [2010]). Lightning discharges of this energetic positive polarity are more rare [*Zhou et al*., 2012a, 2012b] but notorious for destroying wind turbines during winter thunderstorms in Japan, forcing national regulation for adoption of higher standards of lightning protection of wind turbines [*Shindo et al*., 2012]. In general, when the charge regions of the cloud are lower, the chance to initiate upward lightning from tall object increases. This is common in winter storms.

Experience with wind turbines installed all over the world has shown how a particular design of the lightning protection system of a wind turbine can perform very differently in areas with a different climatology of storms (see technical report *IEC 61400-24* [2002]). Characteristics in terms of number of flashes, ratios of upward and downward types, current polarity, peak currents, and energy are the main parameters that determine the effectiveness of a protection system. Local effects can favor a larger number of lightning incidents in particular wind turbines in the same farm. Furthermore, the wind energy industry is migrating toward the installation of wind turbines in the sea, despite the lack of experience regarding lightning and offshore wind turbines [*Braam et al*., 2002].

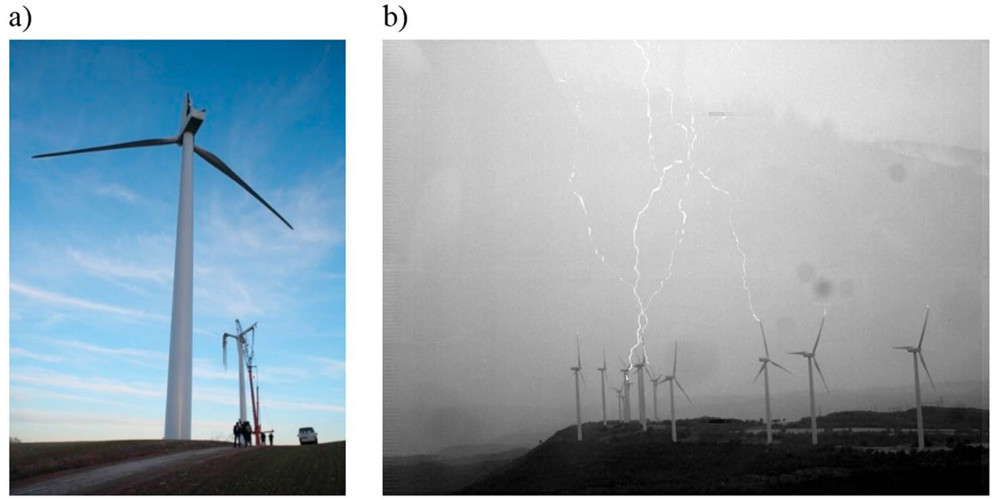

Figure 1. (a) Example of lightning damage to blades of two wind turbines due to a winter storm in the northeast of Spain in 2009. (b) Integrated frames of a high-speed video (available in the supporting information). Three upward positive lightning leaders progressed from rotating wind turbines. Also three wind turbines showed short-lived aborted leaders. The event occurred in the same wind farm as in Figure 1a on 1 July 2012.

The uniqueness that defines a wind turbine in comparison with other man-made tall structures is the rotating blades. Almost 40% of the total turbine height is in rotation which makes it a very special man-made structure. Blades are commonly made with composite materials such as glass fiber and carbon-reinforced plastics. Most blades are simply protected against lightning by means of one or several discrete air terminals and down conductors. Blade tips can reach velocities over 100 m s^{-1}, in the case of 50 m long blades making 18 rpm. More recent blades may have a length of more than 70 m which is comparable in size with the wingspan of the Airbus A380 [*Radicevic et al.*, 2012]. The extensive use of composite materials and the high exposure to lightning attachments can produce severe damage leading to a collapse of the blade when the lightning protection system fails (e.g., punctures on shells and internal arcs). Figure 1a shows an example of severe lightning damages to two wind turbines in the northeast of Spain during a winter storm. A growing number of studies speculate whether a rotating wind turbine is more susceptible to lightning strikes than stationary turbines [e.g., *Rachidi et al.*, 2008; *Wang et al.*, 2008; *Radicevic et al.*, 2012]. *Wang et al.* [2008] found that a rotating wind turbine tends to have a higher chance of initiating an upward leader than a static tower of similar height. More recently, *Wilson et al.* [2013] conducted an experiment with video cameras around a wind farm and current measurements at the blade roots. They suggested that a rotating wind turbine has a larger attractive radius than the expected one for a stationary tower of similar height. For a 125 m wind turbine, they suggested an attractive radius of 276 m in contrast to the predicted (from 160 m to 200 m). Actually, the suggested attractive radius was similar to a 231 m radio tower. In the laboratory, *Radicevic et al.* [2012] experienced higher flashover voltages (up to ~14%) for a rotating scale model than when it was stopped. But in early laboratory experiments with other setups, *Brook et al.* [1961] showed how by introducing fast-moving wires into high electric fields the chance of triggering sparks increased, and in that way it would be possible to trigger lighting by rockets trailing grounded wires. Although high-voltage laboratory experiments with long sparks provide valuable knowledge, the representation of all phenomena that allows a wind turbine to trigger lightning is very difficult to achieve.

This paper provides new observations with the lightning mapping array and high-speed video of atmospheric electrical phenomena/discharges related to wind turbines. Long-lasting periodic detections of VHF sources related to the rotating wind turbines are presented. A rare upward/downward flash triggered by a wind turbine is analyzed and discussed. Next, a high-speed video record of simultaneous upward positive leaders from several wind turbines is shown. Finally, the possible effects of the blade rotation on the increase of the production of electrical discharges are discussed. The results in this paper are valuable for the understanding of the initiation of lightning and development of lightning flashes triggered by complex rotating structures.

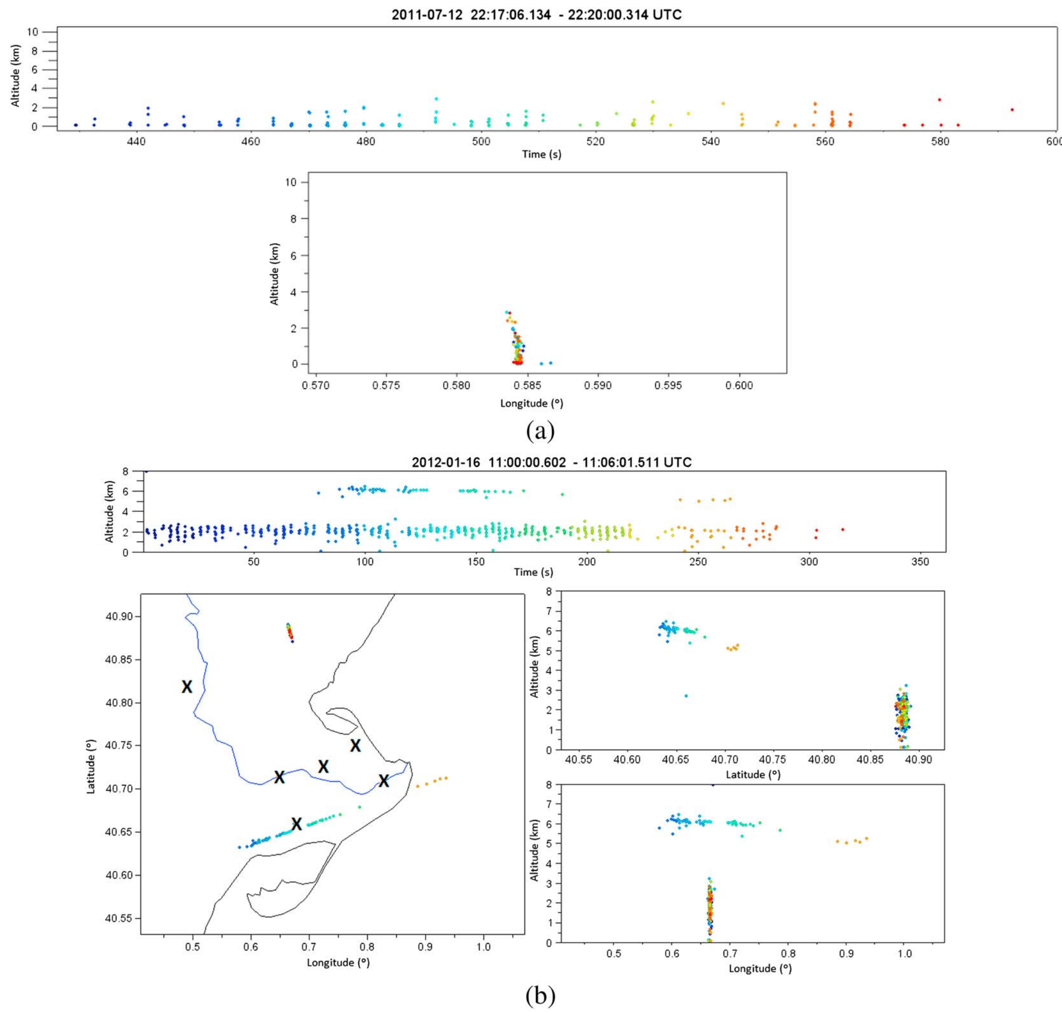

Figure 2. Two examples of repetitive detections of upward discharges from wind turbines. (a) Segment of about 3 min during 12 July 2011. (b) Segment of 10 min during 16 January 2012. In this period emissions produced by electric discharges in a plane were also detected (trace at ~6.5 km). The (cross) symbols in the plan view indicate the locations of the ELMA stations.

2. Observations

In the summer of 2011 the Ebro 3-D Lightning Mapping Array (ELMA) was installed on the east coast of Spain. This advanced system maps radio emissions of lightning channels in three dimensions by the time-of-arrival method in the very high frequency range [e.g., *Rison et al*., 1999; *Thomas et al*., 2004; *Krehbiel et al*., 2008; *Coleman et al*., 2003] and is the first such system established in Europe. Surprisingly, shortly after installation, the first data showed remarkable events related to wind turbines on nearby hilltops (350–650 m above mean sea level). Several large wind farms are present within the range of the ELMA. This array has sensor-to-sensor distances of only 5 to 20 km, and the wind farms of interest are located less than 12 km from the network center. Considering the Friis transmission equation [*Friis*, 1946], the ELMA would be sensitive enough to detect source powers at a level of 4 mW at the wind farm location.

The analysis of time series data showed periods of time with detections emerging from low altitudes at regular intervals of 3.15 s. These detections consisted of multiple sources and lasted roughly 100 ms, and most sources were mapped at altitudes below 2 km. This altitude may in reality have been lower due to the vertical accuracy of the ELMA at low elevations. Following methods devised by *Thomas et al*. [2004], the minimum vertical error for the detections in the studied wind farm would be ~820 m. The geographic coordinates of these detections coincide to within tens of meters with the locations of hilltop wind turbines. Figure 2a presents a segment of 3 min with these periodical detections. The cadence of the detections corresponds to the time

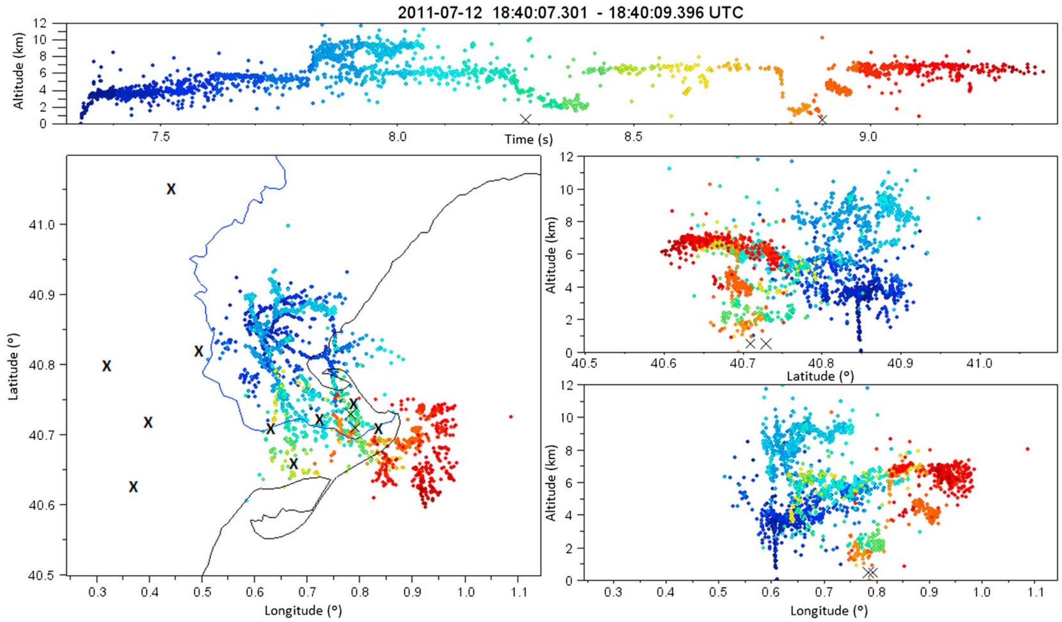

Figure 3. ELMA sources of the upward flash on 12 July 2011 originating on a wind turbine and terminating at ground. The (cross) symbols in all the views indicate ground strokes detected by LINET VLF/LF network [*Betz et al.*, 2004]. The (cross) symbols in the plan view indicate the locations of the ELMA stations.

between each blade tip reaching the highest altitude. During the first year of ELMA operation the situation has occurred several times. In one of the cases, on 16 January 2012, it lasted for more than 1 h. None of these repetitive discharges were detected by any of the regional lightning detection networks. The radiated power of these detections measured by the ELMA was about −5 dBW which is very low in comparison to the typical peak power radiation of lightning (from 0 dBW to 40 dBW) indicated by *Thomas et al.* [2001]. This means that these discharges carry very low currents and did not produce return strokes. On the other hand, they must be much stronger than coronas produced by other objects. Coronas from tall structures and power lines were not detected by the ELMA. Five ELMA stations are needed to produce a source.

When conditions are right, an upward leader from a ground-based object can grow into a full lightning discharge. In general, flashes initiated by upward negative leaders are much less frequent than those initiated by upward positive leaders. As an example, at the Gaisberg tower in Austria only 4% [*Zhou et al.*, 2012b] of the flashes are initiated from the tower by a negative leader. On 12 July 2011 the ELMA detected a rare flash initiating at a wind turbine and terminating at the ground 20 to 25 km away. The mapping of this flash is displayed in Figure 3. This flash initiated as an upward negative leader growing into positive charge and like most negative leaders, radiated strongly in the VHF radio frequency band. The upward propagation speed of the leaders was larger than 10^5 m s^{-1}. In the cloud, negative and positive leaders branched out toward the southeast at an altitude of 5–6 km. The mapping of leader activity revealed a layer of negative charge at altitudes of ~5 km. All this activity occurred in the same flash which in general terms initially brought negative charge upward and later lowered negative charge from a higher negative charge layer. This is a very rare type of flash not reported before and could be classified as a ground-to-cloud-to-ground flash. The relevance of which is the production of extra lightning strikes within a few tens of kilometers around tall objects, which without their presence may not have occurred.

During the 2012 campaign a high-speed video recording of upward leaders from rotating turbines was obtained (Figure 1b). Unfortunately, this case occurred outside the range of the ELMA network. In the video three simultaneous positive leaders are observed to progress upward at speeds of ~1.5×10^4 m s^{-1}. The leader channels were dim and at times not visually distinguishable. Lightning channel brightness, temperature, and currents are closely interrelated. This suggests that the leaders had very low electrical currents during their growth, which is consistent with low ELMA-detected source powers. Since no surges of brightness were observed, the currents involved were continuous. The tips of the leaders were brighter indicating intense ionization and exhibited diffuse ends marking the streamer zone. As the leaders reached higher altitudes, some of them branched and became brighter. Only one of the upward leaders remained, and recoil leader activity started at higher altitudes. In addition to showing stable leaders, Figure 1b shows three wind turbines with short-lived aborted leaders which progressed only ~7 m. The occurrence of leaders at the same time and in a close proximity (less than 300 m) indicates a poor screening effect between them. This fact is of importance in the assessment of the exposure to lightning of individual wind turbines.

3. Effect of Blade Rotation

The observations provided by the ELMA and the recorded video support the hypothesis that conductive moving objects can initiate stable lightning leaders more easily than static objects. Wind turbines experience a combination of two factors that aid the initiation of leader discharges. The first factor is that blade tips avoid the accumulation of self-produced space charge due to their rotation. The blades are therefore exposed to stronger local electric fields than static objects. In a "standard" thunderstorm tripole electrical structure [*Williams*, 1989], the negative midlevel charge causes an upward directed electric field at the ground. In tall grounded objects the local electric field can reach such high levels that positive electrical coronas can develop, a stage which could proceed the production of positive leaders. However, space charge (ionized air) produced by corona suppresses the electric field around an object, inhibiting the formation of new coronas and leaders. Positive space charge consists of ions with mobility much lower than electrons [*Bazelyan and Raizer*, 2000]. In the case of fast-moving objects like rockets with a trailing ground wire, the electrode can escape from the bulk charge produced by corona and is then exposed to stronger electric fields [*Brook et al.*, 1961]. This has also been observed experimentally in moving electrodes in the high-voltage laboratory [*Nagai et al.*, 1983; *Brook et al.*, 1961] and has been known for a long time in rocket-triggered lightning [*Newman*, 1958] where lower rocket speeds are less efficient in triggering lightning [*Uman and Krider*, 1989]. This concept applies to aircraft as well [see *Vonnegut*, 1965], even though these conductors are not grounded.

Figure 4a illustrates the case of a static object where the ion charge created by corona q_c is accumulated above the tip distributed along the highest electric field with drift velocity (μE) and small ion diffusion. Approximately, the altitude reached by the corona charge in a certain time will be μE_t. The local wind will also affect the real ion distribution. When the rotor blade is turning, the speed of the tip needs to be greater than the drift velocity (μE) of small ions produced by corona in order to escape. The mobility [*Aleksandrov et al.*, 2002] of light-weight ions is $\mu \approx 1.5 \times 10^{-4}$ m^2 V^{-1} s^{-1}. A midsize blade of 40 m length rotating at a few turns per minute attains speeds of about 30 m s^{-1} , much faster than the small ion average drift speed of a field of several tens to a few hundreds kV m^{-1}. Due to the rotation, the corona charge q_c is distributed in layers with density ρ_c. In such a case the charge amount just above the tip at any position is much lower than in the stationary case. The smaller the charge above the tip, the higher the electric field will be. Figure 4b depicts the likely distribution of charge produced by the rotation. Since the charge injected into the air drifts with the electric field, it will form radially periodic features separated by a distance *d* related to the rotation speed and the ion drift.

The second factor to consider is that blades are made with insulating composite materials which can accumulate charge. *Salmela et al.* [2013] analyzed the charging of composite frame helicopters at low flight altitudes (12–24 m) under different weather conditions. They found that the amount of charge depends on many factors including the number, the speed and size distribution of the particles, and the surface and speed of the rotor. In a study of corona discharge in a composite aircraft, *Fu et al.* [2008] stated that airplanes fabricated with composite materials have a larger electrostatic accumulation capacity than metal ones. In addition, triboelectric charging can be very efficient in fast-moving objects ($>$ 10 m$\cdot$s^{-1}) when the interaction with water, sleet, and ice occurs [*Illingworth and Marsh*, 1986]. In some wind turbines the blades are not directly connected to Earth, and they utilize spark gap systems to transfer lightning currents to ground. This spark gap method is often used because of the difficulties in firmly grounding a rotating object. Wind turbine maintenance workers reported repetitive and loud sparks in these spark gaps during certain weather conditions, even under fair weather. They attribute it to triboelectric charging. Safety must be considered continuously during work within the rotor hub or blades. Firm evidence of blade electrification during fair weather is still not available. Triboelectric processes may have some contribution to blade charging specially during rain and snow. In addition, triboelectric charging would help or compete with

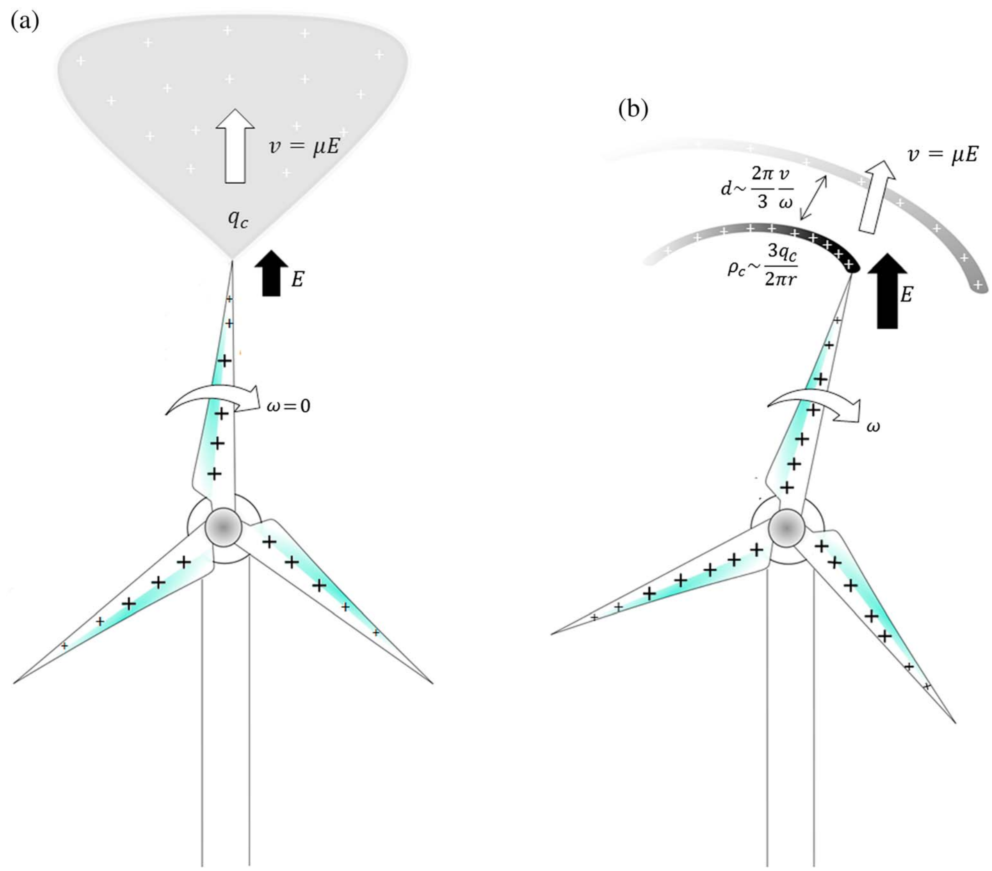

Figure 4. Stationary and rotating wind turbines beneath a thundercloud. (a) Case of static tower or stationary wind turbine. The produced corona charge (q_c) produced lowers the electric field on the tip inhibiting the occurrence of a streamer. (b) A rotating wind turbine will escape from the deposited space charge (q_c) and reduce the charge density (ρ_c) at any position near the tip. The charges are distributed as periodical structures separated a distance *d*. The electric field at the tip is higher on account of its smaller corona charge ρ_c density.

induction charging depending on the polarity of the background electric field. But further investigations are needed to confirm its significance.

In any case, the effect of rotation provides an electric field growth rate which is necessary for allowing the initiation of stable lightning leaders [*Bazelyan and Raizer*, 1997]. Field enhancement and growth in time are also produced when a nearby lightning flash neutralizes cloud charges allowing the initiation of upward lightning leaders from tall grounded objects [*Warner et al.*, 2012] (case in Figure 1b). As a result, two types of upward lightning occur: events induced by nearby lightning flashes (Figure 1b) and self-initiated events (Figure 3). In both types, the rotation would favor the initiation of lightning.

4. Conclusions

VHF radio frequency emissions detected by a Lightning Mapping Array and theoretical discussion confirm that rotating wind turbines can produce electrical discharges more easily than static objects with similar height. Wind turbines are a very particular kind of tall object with moving parts. Efficient power generation requires the use of long lightweight blades. Composite plastics and carbon fibers are being used in the construction of blades, but even though blades are equipped with air terminals and down conductors in order to protect against lightning, such composite materials are more easily damaged than aluminum commonly used in aircraft. The radio frequency emissions of discharges mapped by the Ebro 3-D Lightning Mapping Array are similar to those observed from isolated flying objects and grounded rockets used for triggering lightning. This new type of man-made object reconfirms the idea proposed more than 50 years ago that fast-moving conductors can easily trigger lightning.

We have provided a conceptual framework identifying the evasion of space charge by an object with a speed surpassing the ion drift speed. The framework can be used to improve the design of wind turbines with regard to lightning attachment and damage prevention and to determine possible modes for operation during thunderstorms causing in the lowest probability of lightning strikes with large currents, which cause the most costly damage. The theory suggests that slower rotation makes upward lightning less likely. The main mechanism of charging that a blade experiences under a thunderstorm is attributed to electrostatic induction enhanced by the movement of the blade and its composite materials. In addition, triboelectric charging has been speculated to make some contribution. If triboelectric charging is produced, it results in a buildup of positive potential resulting stronger fields when negatively charged precipitation particles are overhead. But farther research of the significance from triboelectric charging is still needed.

The frequent upward directed discharges from wind turbines are poorly detected by conventional lightning detection networks and therefore have often been underestimated in risk studies. The capability of mapping upward leaders by the LMA offers a unique opportunity to investigate the frequency of events and the favorable conditions of occurrence. Moreover, the high-speed video record showed a poor screening effect between the developments of upward leaders from wind turbines at close distances. This needs to be considered when studying the initiation of leaders from multiple tall objects on the ground and in the risk assessment of lightning to wind turbines.

Finally, as wind turbines enhance conditions for the triggering of lightning artificially, given a background electric field provided by a thundercloud, it raises the question to what extent this anthropogenic cause influences regional lightning rates.

Acknowledgments

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