The Response of Towers and Other Structures to Nearby Lightning

Lothar H. RUHNKE¹, Vladislav MAZUR², and Silvério VISACRO³

¹University of Oklahoma, Norman, OK, USA
e-mail: LHRuhnke@aol.com (corresponding author)
²National Severe Storms Laboratory, Norman, OK, USA
³Lightning Research Centre, Federal University of Minas Gerais, Belo Horizonte, Brazil

Abstract

This study describes an attempt to evaluate the potentially hazardous effects on tall structures from nearby cloud-to-ground flashes by conducting measurements of currents and ground potentials on structures during thunderstorms. The analysis of these measurements has shown that the layout of the elements of ground structures and their connections within a grounding grid of the installation have profound effects on magnitudes and polarities of induced currents and voltages. Understanding of the factors affecting the response of tall ground structures to nearby lightning flashes, and therefore correct interpretation of induced lightning effects on a particular installation is crucial for improving the design of grounding systems of the installations.

Key words: lightning, grounding, lightning hazards, induced effects, lightning measurements.

1. Introduction

Hazardous effects of lightning are usually attributed to the impulse phase of the return stroke current and continuing current that follows cloud-to-ground flashes during their attachment to a ground structure. There is, however, a significant percentage of reported lightning-related damage to structures that is not associated with direct lightning strikes (lightning attachments) (Diendorfer 1990). Among the possible causes for these instances of damage may be upward leaders from the structure, or induction currents, both as effects of nearby lightning flashes. It is expected that the upward leaders would start from the same protruding elements of the structure both in case of
lightning attachment and of lightning nearby. Therefore, if the upward leaders are hazardous, the damages to installations may be similar in both cases. The direct hazardous effects could be from upward leader current pulses of reported maximum values up to 23 kA (Miki et al. 2005).

Indirect lightning effects on tall grounded structures are not well researched, and therefore not considered a lightning protection issue. Evaluation of these effects is the subject of our investigation, which has been conducted in the United States and Brazil. In depicting our data we use the traditional sign convention in atmospheric electricity \( E = \text{grad} \phi \), where \( E \) is an electric field and \( \phi \) is the ambient electrical potential.

2. Instrumentation

A 60-meter tall tower insulated from the ground at the top of a mountain (elevation 1400 m ASL) called Morro do Cachimbo (MCS), near Belo Horizonte, Brazil, a free-standing 90-meter tall tower on a flat ground near Dallas, Texas, and two radar towers, one in Florida and the other in New Mexico, were instrumented for this study (Fig. 1). The measured variables were: the current on a down conductor of the tower, the potential of the grounding system, and local electric field changes produced by lightning flashes. A sensor for slow changes in the electric field (\( \text{dE} \)) was connected to the input of an A/D converter and had an input time constant of several hundred milliseconds. A similar sensor for detecting fast changes of the electric field (\( \text{dE/dt} \)) had a time constant of 10 microseconds. \( \text{dE/dt} \) pulses served to trigger data recording of lightning events. An electric field mill was used at the MCS and Dallas sites for sensing the stationary electric field from clouds prior to and during the lightning event. A ground potential probe, about 100 meters away from the installation, was a part of the system for monitoring the voltage drop over the grounding impedance of the installation. A current clamp (with range of up to 2 kA) on the down conductor of a tower leg was used to measure the current from the tower into the grounding system.

We have used a PC-based data recording system that consists of an A/D converter with a sampling rate of 100,000 samples per second with a 16-bit resolution, and a GPS system that tags each event with one millisecond accuracy. The local LLS (Lightning Location System) in Brazil and the National Lightning Detection Network (NLDN) in the U.S.A. provided complementary data on cloud-to-ground flashes in the vicinities of our installations.

For studying the effects of lightning on a grounded structure, it is critical to determine the value of the impedance of the grounding system. This is not a trivial matter, especially for the extended grounding grid typical of radar sites. We found that an independent ground point for voltage measurements needed to determine the grounding impedance using a three point system may be located as far as a few hundreds meters away from the installation. For example, at the Morro do Cachimbo site the independent ground point was 150 meters away from the tower. At the three other sites in the United States, it was simply impractical to find the true independent ground due to the close proximity of other structures, so we settled for such points as far away from our installation as we could. Resulting from this compromise, the values of ground impedance at our U.S. installations probably underestimated the actual
ones, because the voltages are lower for the ground points closer to the installations than for the points of the true independent ground.

There was another use of the independent ground point, namely for measurements of the potential of a structure affected by lightning. This potential (called here “the loop voltage”) is the voltage between the ground grid of the installation and a ground not affected by the lightning striking the installation, i.e., an independent ground point. A coaxial cable buried in the ground connected the independent ground probe with the measuring system based on PC.

Fig. 1. Installations used for this study. (a) A tower set on insulators at the Morro do Cachimbo station, Brazil. (b) A free standing tower in Texas. (c) A radar site in New Mexico. (d) A radar site in Florida.
Figure 2 shows our initial set-up for measuring the ground potential change for the case of the induced upward leader emerging from the tower and the case of the direct lightning strike to the tower. In both cases the direction of the current is the same, i.e., positive charges are moving upward. The grounding system potential was $V = I_{RS} Z$ while the measured value of loop voltage on the PC was $V/1000$ where 1000 is the ratio of the resistor value at the remote probe to that at the entrance of the PC.

![Diagram of set-up for measuring a “loop voltage” during a direct lightning strike (return stroke current $I_{RS}$) or an upward leader (current $I_{UL}$) from the tower.](image)

Input resistor at the PC is 50 ohm, while the resistor on the other end of the coaxial line, at the independent ground point is 50 k ohm. $V$ is a potential of the grounding system of the installation. The arrow shows the direction of positive charges flowing in the return stroke or upward leader.

The impedance $Z$ of the grounding system was determined by injecting a current pulse $I$ that simulates a return stroke signal by its rise and decay times, and by measuring the voltage response $U$ over the grounding system. We used test current pulses with peak amplitudes of 10 ampere produced by our own current generator, although in the past we had an experience of using for this purpose a commercially available instrument. For the Morro do Cachimbo site in Brazil our measurements showed a grounding impedance of 28 ohm.

### 3. Results

In the course of our investigation we found that upward leaders from the towers which had measurable values of current were relatively rare. We estimated that only lightning flashes located less than 1 km away from the tower might induce upward leaders, because in order to start an upward leader from a 60-meter-tall tower, the required combined electric field from clouds and nearby downward leader needs to be greater than 40 kV m$^{-1}$ (Aleksandrov et al. 2001).
A vertical tower that has capacitance $C$, effective height $h_{\text{eff}}$, and is in the ambient electric field $E$ acts as a single receiving antenna if it is situated on a plane surface without any obstruction from nearby buildings or towers. For such a structure and for a lightning flash up to a few km away we applied the electrostatic assumption for the electric field to describe effects of electric field changes on induced currents (eq. 1), (Kasemir and Ruhnke 1958).

\[ I = \frac{dE}{dt} \times C \times h_{\text{eff}}. \]  

(1)

For the tower at Morro do Cachimbo with measured capacitance $C$ of 1800 pF and an assumed effective height $h_{\text{eff}}$ of 30 m, the relationship (1) is written as:

\[ I(\text{A}) = 0.05 \times \frac{dE}{dt} (\text{V m}^{-1} \text{ s}^{-1}). \]  

(2)

It should be mentioned also that an isolated single receiving antenna would not have induced currents from magnetic field changes produced by nearby lightning.

The output of the fast antenna ($dE/dt$) can be integrated to yield the electrostatic field. For most cases the integrated $dE/dt$ record, after correction of the record for the time constant of the slow antenna, produced a waveform identical to the output of the slow antenna ($dE$). We used this integration procedure also for verification of the integrity of the sensors. A field mill record was used to calibrate the slow and fast antennas.

When the structure is connected to ground by a single down conductor (as in the case of the Morro do Cachimbo tower), the induced current is consistent in its polarity and magnitude with those polarities and magnitudes obtained theoretically from the fast E-field changes (using eq. 1) produced by return strokes. We discovered, however, that in cases of nearby lightning flashes for three installations in the United States, the induced currents to the ground and also loop voltages exhibited quite different behaviours than that expected during upward leaders from the structure or direct lightning attachments to the structure. Figure 3 shows a case when polarities of the loop voltage and induced current are correct, while Figs. 4, and 5 show examples of records inconsistent with expectations.

We found that the loop voltage displayed a polarity dependence on the location of the return stroke attachment point relative to the direction of the coaxial cable that connects the independent ground point with the ground of the structure (Fig. 6). What this polarity dependence indicates is the existence of an induction loop consisting of the connecting coaxial cable and the ground, which is not a perfect conductor and is penetrated by electromagnetic waves (Fig. 7). With the induction loop present, we actually record the induced open circuit voltage from $dH/dt$ of lightning magnetic field together with the voltage drop over the grounding impedance from the induced current on the tower. Thus, the loop voltage that we measured is, at best, a mixture of the induced voltage in this loop and the ground losses due to the current flowing to ground. The voltage in the loop (made of the coaxial cable and the ground) may be much higher than the voltage drop over the grounding resistance from the current in the mast. An additional contributor to the directional behaviour of the loop voltage might be the voltage drop on the ground due to currents from a lightning propagating into the soil and producing a potential distribution in the neighbourhood of the lightning impact point, i.e., the so-called “step voltage” (Lee 1977).
Fig. 3. The record from a nearby flash in Florida at the range of 0.6 km, Imax = -29.3 kA, with correct polarities of current and loop voltage.

Fig. 4. The record from the nearby flash in Florida at the range of 2.6 km, Imax = 17.5 kA with right polarity of current and wrong polarity of loop voltage.
Fig. 5. A record from the nearby flash at range of 2.3 km and of $I_{\text{max}} = 18.3$ kA showing induced current and loop voltage of wrong polarities.

Fig. 6. Graph illustrating the polarity dependence of loop voltage pulses on the direction to the source of a $dH/dt$ pulse (i.e., the direction to the return stroke of a cloud-to-ground flash), in cases of an induction loop made with a horizontally extended cable to a loop voltage probe at the Florida site. Positive and negative polarity values correspond to flashes in the sector of 90-270 degrees and that of 270-90 degrees relative to the orientation of the installation (North-South), respectively. Flashes from azimuth either 90 or 270 degrees do not produce any induced effect in the loop.
Fig. 7. An induced voltage circuit for $d\mathcal{H}/dt$ of nearby lightning flash made of loop of area $S$ consisted of a central core of the coaxial cable and the ground. (Since the ground is not a perfect conductor, low frequency electromagnetic waves penetrate it.).

Fig. 8. A deep ground rod inside a PVC pipe that insulates the rod from the layer of ground above.

Thus, we discovered that using an independent ground point far away (horizontally) prevented us from obtaining the true value of the ground potential change due to the nearby lightning. The alternative is an independent ground point deep in the ground and practically inside the installation. Our attempts to find an independent ground point deep beneath the grounded mast in Texas did not succeed because we could not insert (manually) an insulated ground rod deep enough to achieve a desirable effect. Thus, so far we were not able to estimate correctly induced effects of a nearby lightning flash on the ground potential of the installation. Currently we are conducting measurements at a new site in Alabama utilizing an insulated ground rod installed at a depth of 30 meters as an independent ground point (see Fig. 8).
Fig. 9. Set-up for current measurements of induced current on a tower from a nearby cloud-to-ground flash. Notice change in direction of the induced current $I_{\text{ind}} = \frac{dE}{dt} C h_{\text{eff}}$ for two stages of a cloud-to-ground flash. Negative leaders and return stroke have the same current polarity. Arrows show directions of propagation for negatively charged downward leader and positively charges return stroke, respectively.

![Diagram of current measurement setup](image)

Fig. 10. Polarity dependence of current pulses to the source direction.

Currents flowing from the tall structure to ground were measured using current-to-voltage transducers clamped around a down conductor of a tower leg (Fig. 9). We determined that the induced current pulses associated with fast electric field changes during the return strokes of nearby cloud-to-ground flashes are of much greater amplitudes than those expected from the theoretical considerations (see eq. 1) for a given tower with a given ground impedance. The recorded current pulses were sensitive also
to directions to the current source (Fig. 10). This phenomenon characterized current measurements at all three installations in the United States, but not at the MCS tower in Brazil.

We found that there is a common feature in the configurations of the grounding systems in the U.S sites, namely, the extended ground grid connecting the down conductors (more than one) of the tower with the down conductors at other buildings in very close proximity to the tower (see Fig. 11). These are conductor loops subjected to induced currents from magnetic field changes of return stroke signals. On the other hand, the tower in Brazil that is resting on insulators had a single connection to the ground, and its grounding grid is of a small size and symmetric in relation to the tower.

Fig. 11. Induction loops are formed by down conductors and other elements of the grounding system above and below the ground. Induced voltage at this Florida site is produced mainly by dH/dt penetrating the loop, which is in the plane (W to E) perpendicular to axis 350-170 deg AZ.

The directional dependence of induced current pulses in the U.S. sites brings into question the validity of using current measurement with magnetic link sensors at structures with multiple grounding conductors for estimating the current in lightning channels. In view of this discovery, it was interesting to compare our measurements with those obtained at structures with a single down conductor to ground. As expected, the data from the MCS tower in Brazil that has a single down conductor did not contain any directional effects in the records of induced currents. However, data from yet another mast with a single down conductor (a lightning protection mast at Indianhead, Maryland), did show, to our surprise, a directional dependence similar to those in tall structures with multiple grounding systems. Closer examination of the Indianhead site showed that this installation had a nearby building with its grounding system connected to the grounding grid of the mast. The presence of this building determined the directional dependence of induced currents. Figure 12 depicts the polarity dependence of return stroke signals sensed by a current probe on the Indianhead mast with a single down conductor but situated near a well grounded building.
This finding proves that asymmetries in installations, e.g., some other structures in the close proximity to single masts, can have interacting effects if grounding resistance between mast and associated structure (building) is low enough. Such interactions are widely known in radio antennas, e.g., in Adcock antennas that rely on the interaction of two vertical antennas for producing a directional receiving pattern. As in Adcock antennas, the induced current flowing in an asymmetric installation has much greater amplitude than that in a single isolated mast, which is an analogy of a whip antenna. Our three installations in the United States have asymmetric structure, which explains why the induced current values we measured were so much higher than those expected under the electrostatic assumption (eq. 1).

Most of the above problems with measurements of induced currents and voltages do not exist in cases of direct strikes to structures or upward leaders from structures. However, direct strikes to the installations under study were rare and even upward leaders solely due to cloud electric fields did not occur during our studies. We anticipated that upward leaders from a tower would occur occasionally when either cloud electric fields of high magnitude were present and/or downward leaders preceding return strokes occurred within 1 km of our observation sites. In the latter case, upward leaders would be of short duration and would stop when the return stroke process starts. Figure 13A shows the current record of such upward leader from the Indianhead tower, with a cloud-to-ground flash reported by NLDN being 0.7 km away. Negative current pulses with a noticeable DC component rising with time appeared about 1 millisecond prior to the return stroke process that started at time zero, when the downward leader reached ground. A positive potential near the structure produced by positive charges on the return stroke channel killed the upward leader progression.

Figure 13B depicts a more frequent case of a similar nearby cloud-to-ground flash, but without an upward leader. The difference between these two cases is in the
presence of high ambient electric field in the case depicted in Fig. 13A, and the absence of such field in the case depicted in Fig. 13B, although the downward leader of a nearby cloud-to-ground flash was in evidence in both cases.

4. Conclusions

The response of towers and other tall ground structures to nearby lightning flashes in form of induced current and voltages, although understood in principle, is poorly researched in regards to quantitative relationships between physical processes and structures involved. We found that induced currents in tall structures from nearby cloud-to-ground flashes may be strongly influenced by the design of the grounding system. The ways the elements of the grounding system are connected affect the magnitude and polarity of induced current pulses. We have found that the induced currents on towers or complex installations with asymmetric structure of the grounding system may be orders of magnitude higher than the induced currents produced by fast field variations (dE/dt) from nearby lightning flashes. Our interpretation of this finding is that the asymmetric installations connected through a grounding system with low impedance are acting like Adcock antennas. Then the induced current pulses of high amplitudes flow along the external elements of the structure, and may affect sensitive devices installed there.

Jones et al. (2004) who applied peak current magnetic cards (bandwidth of more than hundreds of MHz) to monitor currents on the external down conductors of lightning protection systems in the United Kingdom reported presumably induced current pulses from nearby lightning of up to 120 kA. Perhaps our explanation of the nature of very high values of induced current pulses in asymmetric installations can be applied to interpret the measurements in UK. This is under the realistic assumption that the lightning protection systems of munitions storage sites in UK, with its numer-
ous down conductors, resemble the asymmetric structures connected by a low impedance grounding grid.

The effects of nearby lightning on a ground potential of the installations of different configurations still remain to be determined, because our initially selected method of measuring this potential resulted in significant contaminations from several unrelated variations of lightning electric and magnetic fields. We intent to conduct measurements of the ground potential change using a point of independent ground deep down at the installation site, with a minimum horizontal exposure of a connecting coaxial cable.

Acknowledgments. This research was sponsored in part by the FAA under a cooperative agreement with the National Severe Storms Laboratory. We thank Vaisala, Inc. for complimentary NLDN data in support of this research. We appreciate the contribution of Christopher Karabin of the Indianhead Division of the Naval Surface Warfare Centre who provided Figures 12 and 13 from his data base. The invaluable help by Renato de Oliveira and Marcelo Felipe, graduate students of the Federal University of Minas Gerais, in maintaining the observation site at Morro do Cachimbo, Brazil, conducting data acquisition there, and assisting in data processing is deeply appreciated.

References


Received April 17, 2009