FDTD Simulation of Field-Reduction Effect at Ground Due to Corona at Lightning-Triggering Wire

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Abstract

The effect of an upward-extending wire used for artificial lightning initiation from natural thunderclouds and the corona space charge emanated from this wire on the close electric field (prior to lightning initiation) on the ground surface has been examined using the FDTD method. When the wire-top altitude is 200 m, the reduction of upward-directed electric field E_z at a horizontal distance of d=60 m is 15, 23, 28, and 38% relative to the background value at ground surface of 10 kV/m for corona radii, r = 0.27, 2, 4, and 10 m, respectively. These calculated results agree reasonably well with measurements.

1. Introduction

The artificial triggering of a lightning discharge from a natural thundercloud to a designated point on ground by means of the so-called rocket-and-wire technique [1-3] has been used for studying various lightning processes and effects and for testing the validity of various lightning models and lightning locating systems.

Nakamura et al. [4] have measured the upward- or downward-directed electric field on the ground surface at d=40 or 57 m from an upward-extending grounded triggering wire (prior to lightning initiation) along with the corresponding current at the bottom of the wire for several events in 1979 to 1982. The electric fields decreased in absolute value with increasing the wire-top height. For example, the magnitudes of electric fields at d=57 m for two events reduced from 5.7 kV/m to 3.9 kV/m (30% reduction) and from 7.4 kV/m to 1.6 kV/m (80% reduction) when the wire-top attained an altitude of 200 m. In the latter event, the electric field decreased to zero when the wire-top attained an altitude of about 230 m. In another event, the polarity of the electric field measured at d=40 m changed during the extension of triggering wire. The slowly-varying currents measured at the bottom of the triggering wire were up to 5 to 10 mA. Further, Nakamura et al. [4] used the charge simulation method (CSM) [5] to compute the electric field at ground vs. the length of triggering wire assuming that the induced charge (found by integrating measured current) was distributed within 1- or 4-m radius cylinder simulating the corona sheath surrounding the wire. For two events, they have shown that the CSM-calculated electric-field reduction at d=40 m agrees well with corresponding measured electric-field reduction.

Biagi et al. [6] have shown, from their measurements for six flashes in Florida, that the upward-directed electric field on the ground surface at d=60 m from an upward-extending grounded triggering wire decreases (prior to lightning initiation) by about 30 to 75% with increasing the rocket altitude from ground level to a height ranging from about 120 to 300 m, while the simultaneously measured field at d=350 m decreases by about 9% at most.

The above observations and computations indicate that the reduction of upward- or downward-directed electric field in the vicinity of an upward-extending grounded triggering wire might be due to the shielding effect of the triggering wire and the corona space charge emanated from the wire (corona sheath). However, as of today, relative contributions to the shielding effect of the wire and the corona space charge are not fully understood.

In this paper, using the finite-difference time-domain (FDTD) method [7], we will examine the effect of an upward-extending triggering wire in classical lightning triggering and the corona space charge emanated from this wire on the close upward-directed electric field on the ground surface. Also, we will evaluate the charge transfer from the ground and the corresponding current in the triggering wire.

2. Model

Figure 1 shows the configuration including a grounded perfect conductor, representing a triggering wire and its corona sheath (if any), which extends upward at a constant speed of v = 200 m/s in a quasi-static upward-directed electric field, to be analyzed using the FDTD method in the two-dimensional (2D) cylindrical coordinate system. Perfectly-conducting cylindrical tubes of height 20 m, thickness 2 m, and inner radii 40, 80, 120, …, 960 m, which are located on the ground surface, coaxial with the upward-extending conductor, simulate the presence of corona-space-

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charge layer that is likely to be emitted from irregularities on the ground surface such as grass, bushes, and so on [8]. The quasi-static upward-directed electric field is formed between two perfectly conducting disks of 1 km radius and 1 km apart by a 30-kV/m uniform vertical electric-field source placed at the periphery of the cylindrical computational domain. Owing to the shielding effect of 20-m high cylindrical tubes, upward-directed electric field on the ground surface is about 10 kV/m, while it is 30 kV/m aloft. In order to suppress oscillations, due to successive reflections between the cylindrical electric-field source and the vertical axis of the cylindrical computational domain, a lossy cylindrical tube of thickness 4 m and conductivity 1 S/m is placed in front of the cylindrical electric-field source (see Figure 1). The actual 2D-working space for the present FDTD simulations is 1 km × 1 km, which is divided into rectangular cells of 2 m × 5 m. The time increment is set to 5 ns (but calculated values are taken every 25 ms in order to reduce the amount of output data). The upward-extending grounded triggering copper wire, whose radius is typically 0.1 to 0.3 mm, is represented by a vertical perfect conductor of radius 0.27 m (0.135 times the lateral side length of the rectangular cell employed [9], which is 2 m in the present simulations). In order to examine adequacy of this wire representation, the FDTD calculations were additionally performed for r =0.027 m (≈0.135 × 0.2 m) and 0.2 m with rectangular cells of 0.2 m × 5 m and a time increment of 0.5 ns. The electric-field reduction at a distance of d= 60 m on the ground surface was found to be 12 and 15% for r = 27 mm and 0.27 m, respectively. By extrapolation, it appears that for $r \approx 0.1-0.3$ mm the electric-field decrease would be roughly around 10%; that is, within a factor of 1.5 of that for r = 0.27 m. Since specification of actual wire radius requires unreasonably large computation time, we will employ r = 0.27 m in the rest of this paper. The presence of thin Kevlar (insulating) coating of the wire is neglected. The conductor stops extending when it attains an altitude of 200 m at time equal to 1 s. The corona space charge emanated from the triggering wire is represented by a perfectly conducting cylindrical sheath of outer radius r = 2, 4 and 10 m. The corona sheath is assumed to extend upward at the same speed as the wire-representing conductor does. The corona sheath was assumed to be perfectly conducting, since the results are not sensitive to variation of its conductivity from 10^{-8} S/m to infinity.

3. Analysis and Results

Figure 2 shows FDTD-calculated variations of upward-directed electric field E_z on the ground surface as a function of conductor-top height at horizontal distances of d= 60, 100, and 340 m from the upward-extending conductor, for different corona-sheath radii ranging from 0 to 10 m. Note that, in this figure, the upward-directed electric field is defined as positive (the physics sign convention). We will use this sign convention throughout this paper. When the conductor-top height is 200 m, E_z at d= 60 m is 15, 23, 28, and 38% lower than the background 10 kV/m at ground level for r = 0.27 m, 2, 4, and 10 m, respectively, while the corresponding reduction of E_z at d= 340 m is only 1, 1, 2, and 2%, respectively. Note that, the reduction of E_z at d= 60 m in the absence of 20-m high cylindrical tubes representing corona-space-charge layer at ground (16, 24, 29, and 40% for r = 0.27 m, 2, 4, and 10 m, respectively) is almost the same as that in their presence. These calculated results agree reasonably well with E_z measured by Biagi et al. [6] at d= 60 and 350 m from the triggering wire (prior to lightning initiation). The reduction of measured E_z at d=60 m ranges from about 35 to 50% for wire-top height equal to about 200 m, which correspond to $r \approx 10$ m (or more) in calculated results. This indicates that the reduction of measured E_z in the vicinity of triggering wire, prior to lightning initiation is primarily caused by the presence of corona space charge emanated from the wire, and the radius of corona sheath (assumed to be cylindrical) should be about 10 m or more. Indeed, the conductor of 0.27 m radius representing the triggering wire alone (or with a very small corona sheath) is responsible for only 15% reduction of E_z at d=60 m. This agrees well with the 13% reduction of E_z at d=57 m due to the presence of a 200-m long vertical wire without corona, computed by Nakamura et al. [4] using the charge simulation method (CSM) [5]. Also about 60% reduction of E_z at a close distance (not specified exactly) measured by Standler [10], about 50% reduction of E_z at d=100 m measured by Fieux et al. [11], about 30 to 80% decrease of E_z at d=57 m measured by Nakamura et al. [4] for the wire-top height equal to 200 m, about 3.5-kV/m decrease of E_z at d=75 m measured by Liu et al. [12], and about 8-kV/m decrease of E_z at 30 m measured by Willett et al. [13] appear to agree reasonably well with the FDTD-calculated reduction in E_z for larger (more than 4 m) outer corona-sheath radii. Therefore, these measured decreases of E_z at close distances were likely to be primarily due to the presence of considerable corona space charge emanated from the wire.

Figure 3 shows FDTD-calculated time-variations of total charge on the surface of upward-extending conductor for different conductor radii. Note that total charge accounts for both charges residing on the wire and space charges in the surrounding air. The charge magnitude increases with increasing the height of the top of the upward-extending conductor. The charge transferred through the bottom of the wire whose top is at a height of 200 m, mostly to the corona sheath, is about 1.5, 5, 8, and 12 mC for r =0.27, 2, 4, and 10 m, respectively. The corresponding charge transfers in the absence of simulated corona space charge layer at ground (10 kV/m both at ground level and aloft) were 0.5, 2, 3, and 5 mC. Note that the charge transfer reported by Standler [10] for the triggering wire whose top was at an altitude of 550 m is 11.4 mC.

Figure 4 shows currents flowing in the upward-extending conductor for different conductor radii, computed as time derivatives of FDTD-calculated charge (see Figure 3). At time equal to 1 s, when the top of the conductor attains an altitude of 200 m, the magnitude of current flowing into the conductor is about 2, 9, 14, and 22 mA for r =0.27, 2, 4, and 10 m, respectively. The corresponding currents in the absence of simulated corona space charge layer at ground (10 kV/m both at ground level and aloft) were 1, 3, 5, and 7 mA. Note that the currents at the bottom of triggering wire (prior to lightning initiation) measured by Standler [10] and Nakamura et al. [4] were about 10 mA (when the estimated rocket altitude was 550 m) and up to 5 to 10 mA, respectively.

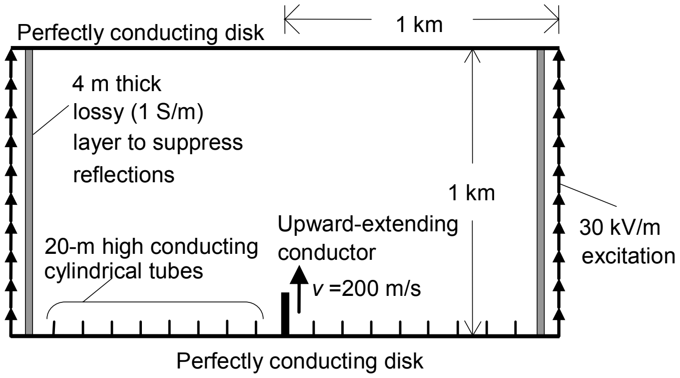

Figure 1. Configuration of a grounded conductor of radius 0.27, 2, 4, and 10 m, which extends upward at a constant speed of v = 200 m/s in a quasi-static upward-directed electric field of about 10 kV/m on the ground surface and 30 kV/m aloft, to be analyzed using the FDTD method. The upward-directed electric field is formed between two perfectly conducting disks of 1 km radius and 1 km apart. Perfectly-conducting 20-m high cylindrical tubes on the ground surface, coaxial with the upward-extending conductor, represent the presence of corona-space-charge layer at ground.

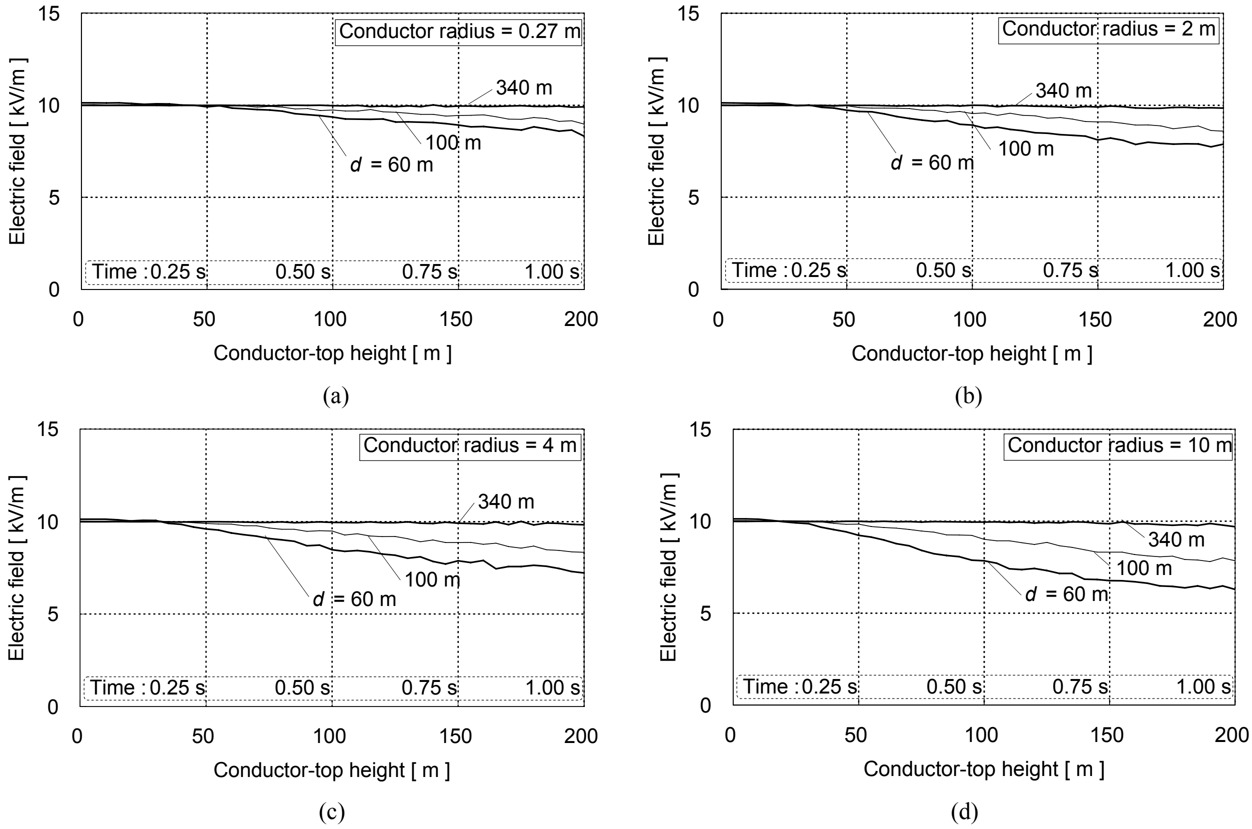

Figure 2. FDTD-calculated variations of upward-directed electric field E_z on the ground surface as a function of conductor-top height at horizontal distances of d=60, 100, and 340 m from an upward-extending conductor, for different conductor radii: (a) 0.27 m, (b) 2 m, (c) 4 m, and (d) 10 m. The conductor extends upward up to an altitude of 200 m, at a speed of v =200 m/s in a quasi-static upward-directed electric field of about 10 kV/m on the ground surface and 30 kV/m aloft.

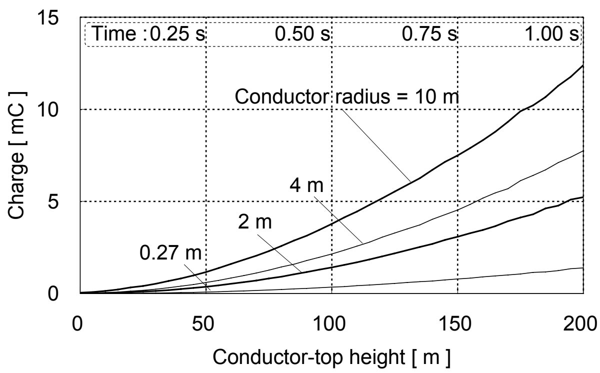

Figure 3. FDTD-calculated time-variations of total charge on the surface of an upward-extending conductor (representing both the triggering wire and its corona sheath) for different conductor radii, 0.27, 2, 4, and 10 m.

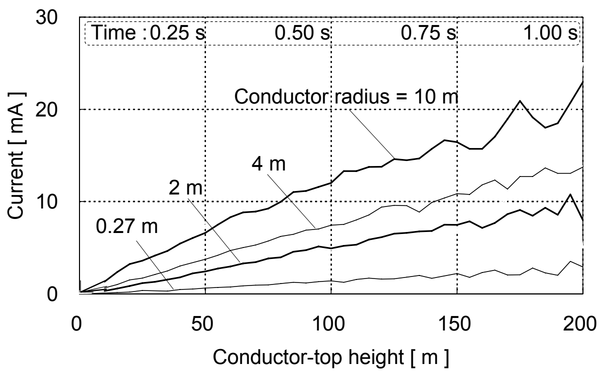

Figure 4. Currents (time derivatives of FDTD-calculated total charges shown in Figure 3) flowing in an upward-extending conductor for different conductor radii, 0.27, 2, 4, and 10 m.

4. Conclusion

We have examined the effect of an upward-extending wire used for artificial lightning initiation from natural thunderclouds and the corona space charge emanated from this wire on the close electric field E_z (prior to lightning initiation) on the ground surface, using the FDTD method. The magnitude of E_z on the ground surface at horizontal distances of d=60, 100 and 340 m from the triggering wire decreases with increasing the conductor-top height. When the conductor-top height is 200 m, the reduction of E_z at d=60 m is about 15, 23, 28, and 38% relative to the background value of about 10 kV/m (at ground level with 30 kV/m aloft) for r =0.27 m, 2, 4, and 10 m, respectively, while the corresponding reduction of E_z at d=340 m is only 1, 1, 2, and 2%, respectively. The observed reduction of E_z at d=60 m ranges from about 35 to 50%, which corresponds to $r \approx 10$ m or more in calculated results. This indicates that the reduction of E_z measured in the vicinity of triggering wire, prior to lightning initiation, is primarily caused by the presence of considerable corona space charge emanated from the wire. For the considered configuration, the total charge transfers from the ground to the wire, whose top is at an altitude of 200 m, are about 1.5, 5, 8, and 12 mC for r =0.27, 2, 4, and 10 m, respectively. The corresponding currents flowing into the wire are 2, 9, 14, and 22 mA.

5. References

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