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Influence on simulation accuracy of atmospheric electric field around a building by space resolution

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ABSTRACT

The actual value of the atmospheric electric field intensification upon the top of a building in continuous space is important for the atmospheric electricity researches but hardly obtained through observations and numerical computations. An extrapolation method has been adopted for estimating the actual value from a fitted formula. This estimated actual value was defined as the extrapolated value, and the relationship between the extrapolated value and the building dimension is obtained. By comparing the calculated value in a certain resolution with the extrapolated value, the systematic error of the calculated value has been found to be a fixed value, which is closely associated with the resolution rather than a structure's dimension. The extrapolated value has a more significant correlation with the smallest mesh spacing of the point chosen for the fitted formula, but less with the number and distribution of the points.

1. Introduction

Although atmospheric electricity is composed of a wide range of electric phenomena in the troposphere, stratosphere, and even in the lower ionosphere (Qie, 2012), the influence of a complex underlying surface on atmospheric electric field is a key problem. The effects of tall buildings on atmospheric electric field intensification play an important role in forming corona layer at or near the ground (Aleksandrov et al., 2001, 2005a,b; Qie et al., 1994; Standler and Winn, 1979), initiating upward leader or lightning (Becerra and Cooray, 2006a,b; Jiang et al., 2013; López et al., 2012; Wang et al., 2012) and calculating lightning rod efficacy (D'Alessandro, 2003a,b; Ilić and Aleksić, 2009; Moore, 1983; Moore et al., 2003). What's more, the intensification is caused by the instrument itself, so that the atmospheric electric field as measured by field mill needs to be corrected before it can be used (Bennett and Harrison, 2008; Minamoto and Kadokura, 2011; Qie et al., 2009; Serrano et al., 2006; Soula and Georgis, 2013; Xu et al., 2013). Thus, an accurate measurement or calculation of atmospheric electric field intensification, becomes a critical task for the scientific researcher who is interested in the problems mentioned above. Because of the limitation of the current field observation, the electric field around the buildings can hardly be measured effectively. However, with the rapid development of computer technology, the numerical calculation has been widely used to acquire the electric field around a building or a lightning rod. The purposes of the numerical calculations in existing literatures are mostly focused on the following two categories: 1) the magnitude of the electric field which is intensified by the building and 2) the relation between the electric field intensification and the building dimension.

The former category is mostly concerned researchers who study the effects on other atmospheric physical processes of the atmospheric electric field intensification caused by complex underline surface. It is important to calculate the electric field threshold value of corona ions releasing in corona discharge numerical simulations and air breakdown in upward leader initiating and propagating models (Aleksandrov et al., 2001,

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2005a; Bazelyan et al., 2009; Becerra and Cooray, 2006b). What's more, the value of electric field intensification upon top of a building or a lightning protection rod is one of the determining factors to calculate the probability of lightning strike and the radius of protection of the lightning rod (Carrara and Thione, 1976; Moore et al., 2000; Petrov and Waters, 1995). Researches about the latter category mainly pay attention on the relationships between electric field intensification and a building's or a structure's dimensions. Hartmann (1984) discussed the relation of a tip's radius with the local electric field at the tip of a rod for seeking the self-sustained condition of stable corona discharge. D'Alessandro (2007, 2003a,b) showed the variations of electric field intensification caused by different dimensions of a building or a lightning rod, and different locations of rod placed on a building. Furthermore, the electric field intensified by different kinds of structures such as cylinder (Eriksson, 1979), ellipsoid (Moore, 1983) and so on, was also computed.

No matter whether the charge simulation method, the finite element method or the finite difference method is used, the value of the field intensification of a certain building or the relationship between the values and the dimensions was computed by dividing the space (in the following, we use continuous space which means that grid spacing is infinitesimal and approaches to zero, to express the space mentioned above in order to distinguish with discrete space) into discrete grids in numerical models. However, the calculations were different in different mesh spacing (D'Alessandro, 2003b; Tan et al., 2006; Tao et al., 2009). The uncertainty of the result caused by mesh spacing is unavoidable in numerical simulated works. And it will make a great negative impact as follows: 1) the universality of the calculation result and 2) the comparability of the results in different numerical studies. In choosing the correct threshold values of upward leader or lightning initiation and corona discharge on objects, the values would be different in numerical simulations with different grid spacing (Aleksandrov et al., 2006; D'Alessandro, 2003b; Lalande et al., 2002; Lalande and Mazur, 2012; Mazur et al., 2000). Thus, two important but hard problems have to be resolved: 1) how to reduce this uncertainty in numerical simulation and make the calculation results or some threshold values of different numerical simulations more comparable, and 2) whether the value of the electric field intensification can be computed or estimated in continuous space.

This paper aims to resolve these problems via various fine-spatial resolution calculations. Applying the FDM (finite difference method) to resolve Laplace's equation, we calculated the value pf the field intensification which is produced by structures in different resolutions and then estimated the value in continuous space. Furthermore, according to the obtained values, the systematic errors in different resolutions were enumerated. The factors affecting the estimated value were also discussed in our paper.

2. Model and method

In this paper, the study is mostly focused on the method of estimating the value of electric field intensification factor on symmetric structure in continuous space and calculating the systematic errors in different resolutions. The space resolution adopted in simulation is an essential factor for calculation. The finer resolution is closer to the continuous space. Considering limiting of computer, the finer resolution can be adopted in 2D (two-dimension) model than 3D (three-dimension) model. So, the 2D Atmospheric Electric Field Intensification Model (defined as 2D-AEFIM) has been established. We focus on the electric field upon the cuboid structure's top corner where the intensification is most obvious. The area near the ground surface is considered as the main study area, which range is 400 m × 400 m. In addition, the background electric field (shown as E_0) is assumed as a homogeneous field, without the effect of free charge. The magnitude and the direction of E_0 is regarded as the same as the fair weather electric field near the surface of the Earth (Wallace et al., 2006), which magnitude is averaged ~130 V/m and direction is vertical downward. The atmospheric electric field distribution around the building has been calculated by using Laplace's equation. Five-point finite difference method is used to solve the Laplace's equation under the given boundary conditions in discretization field. Four boundaries of the model are divided into two categories: one bottom boundary, which is formed an equipotential surface of 0 V and composed of earth and well-grounded structure, follows Dirichlet boundary condition; the other three are air boundaries, including two lateral and one top boundaries, all follow Numann boundary condition. And the parameters of the structures, which affect the electric field intensification, are considered as height (H) and width (W).

The grid spacing (delegated as h) in the X and Y directions has been adopt to be equal and 10 different values are set in our simulations. So there are 10 different resolutions for each building pattern to estimate the value of electric field intensity in continuous space. It needs to be declared that the finer resolution is associated with the smaller h and the larger h delegate the coarser resolution in a fixed simulation region.

With a structure present, Laplace's equation, $\nabla^2\varphi = 0$, is solved by using the FDM. Since the number of grid is lager, we use SOR (successive over-relaxation) iterative algorithm to solve difference equation to acquire the potential (Mansell et al., 2002). The iterative formula of potential is as follows:

$$\varphi_{i,j}^{n+1} = \varphi_{i,j}^{n} + \omega\left(\varphi_{i-1,j}^{n+1} + \varphi_{i,j-1}^{n+1} + \varphi_{i,j+1}^{n} + \varphi_{i+1,j}^{n} - 4\varphi_{i,j}^{n}\right)/4 \quad (1)$$

where φ is electric potential, and ω is over-relaxation parameter which has an experimentally determined value in the range of 1 to 2.

This solution provides potential of each grid point over the problem region, shown in Fig. 1. The magnitude of the electric field intensity is computed from potential gradient, $E = -\nabla\varphi$ (D'Alessandro, 2007).

The point of interest on a structure is the nearest point upon the corner of the top plant surface. The electric field intensification factor K_i of that point means the ratio between the magnitude of E of the point and background electric field intensity $E_{0.}$ In this paper, we neglected the impact of corona layer on the electric field intensity over the corner or the tip when the value of the intensified field intensity is greater than the threshold value of corona ion emission. And just focus on the effect of electric field intensification itself. The main variables in our study are as follows: structure height, H; width, W; and grid spacing, h. Multiple non-linear regression fits are carried out on the K_i data to obtain general relations. Given the above information, it can be seen that $K_i = f(h,H,W)$.