Calculation of Current Distribution in the Lightning Protective System of a Residential House

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***Abstract*—The lightning current distribution in the lightning protective system (LPS) of a residential house was experimentally studied in 2004 and 2005 at the International Center for Lightning Research and Testing (ICLRT) [1]. In this paper, the lightning current distribution in the LPS is calculated based on the distributed parameter circuit in the frequency domain. The electromagnetic coupling between the LPS and the lightning channel is taken into account. The lightning channel and the connecting wire between the launch tower and the house are modeled as vertical and horizontal dipoles above lossy ground. An improved discrete complex images method (DCIM) is presented to calculate the electromagnetic field of the lightning channel. The lightning current distribution in the LPS is also calculated by means of the commercial software CDEGS, and the calculated currents in the LPS are compared with those measured.**

***Index Terms*—Electromagnetic coupling, lightning protection system, lightning electromagnetic field, grounding**

I. Introduction

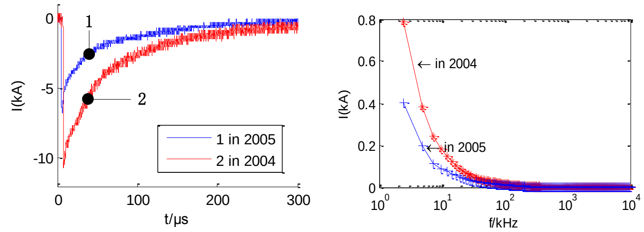
In 2004 and 2005, ICLRT conducted the experiments on the residential house at Camp Blanding, Florida, and obtained the current distribution of the LPS [1-2]. The lightning current distribution of the LPS was calculated based on the lumped parameter circuit theory in the frequency domain considering the electromagnetic coupling between the lightning channel and LPS. Taking into account the effect of lossy ground, the discrete complex image method (DCIM) was employed in the calculation of the lightning electromagnetic field and the computation time has been drastically reduced [3].

In this paper, considering the spectrum character of the lightning injection current, a numerical model is built based on equivalent transmission line networks in the frequency domain, and solved by the circuit topology combined with the transmission line equations. The kernel function of the Sommerfeld-type integral (SI) oscillates seriously in the far field, in order to improve calculation accuracy, we extract the quasi-static items from the kernel function. This method is called improved DCIM. Meanwhile, simulates the LPS by means of the electro-magnetic transient simulation software CDEGS and the calculated currents in the LPS for the two cases are compared with those measured.

II. Methodology

A. Distributed parameter circuit model

The measured injection current waveform and the magnitude spectrum calculated by the Fourier transform are shown in Fig. 1(a) and (b), respectively.



(a) The lightning current waveform (b) The magnitude spectrum
Fig.1. The lightning injection current in 2004 and 2005

It can be seen that the maximum frequency is up to 10MHz. According to the sampling theorem, the maximum frequency is set to 20 MHz and the corresponding wave length is 15m in air and about 5m in the soil, which are comparable with the dimensions of the house. In this paper, the conductors of the LPS are described by using the transmission line model, which are equivalent to a part of circuit topology by replacing the network voltage and current vectors with appropriate transmission line voltage and current vectors. Combining the Modified Nodal Analysis with transmission line equation, we obtain the transient solution of the entire transmission network. The transmission line and circuit parameters can be estimated by means of the approximate formulae given in [6].

B. Electromotive force induced in LPS

The induced voltage in the main loop formed by the LPS above-ground conductors for the configuration is calculated in the frequency domain as:

$$e = -j\omega\oint_l A\cdot dl \tag{1}$$

where A is the magnetic vector potential above the ground level. For a vertical electric dipole over flat, homogeneous lossy ground the magnetic vector potential above the ground level can be expressed in the frequency domain as [4]:

$$A_{vz} = \frac{\mu_0 Idl}{4\pi}\left[\frac{e^{-jk_0R_0}}{R_0} + \int_0^\infty \frac{F}{v_0} e^{-v_0(z'+z)} J_0(\lambda\rho)\lambda d\lambda\right] \tag{2}$$

where J_0 is the first Bessel function of order zero, dl is the length of dipole, λ is the integral variable and the kernel function F are given by:

$$F = \frac{k_1^2 v_0 - k_0^2 v_1}{k_1^2 v_0 + k_0^2 v_1} \tag{3}$$

where $v_0=\sqrt{\lambda^2 - k_0^2}$ and $v_1=\sqrt{\lambda^2 - k_1^2}$, k_0 and k_1 are the wave numbers of air and soil, $k_0^2 = \omega^2\mu_0\varepsilon_0$, $k_1^2 = -j\omega\mu_0(\sigma_1 + j\omega\varepsilon_1)$.

The kernel functions have characteristics of high oscillation and slow decay. For DCIM method, in order to capture the high-oscillation characteristics, requires more meticulous sampling by means of decreasing the sampling interval. In order to capture the slow decay characteristics, requires longer sampling region by means of increasing sampling time. Thus, it would inevitably lead to generate a large matrix in calculation of the complex image coefficient. To avoid this case, we adopt improved DCIM to calculate the SIs. As an example, function F can be decomposed as:

$$F(\lambda)=F(\lambda)\text{-}F_{asy}(\mathrm{v}_0)\text{+}F_{asy}(\mathrm{v}_0)\text{=}\Delta F(\lambda)\text{+}F_{asy}(\mathrm{v}_0) \quad (4)$$

where F_{asy} is the asymptotically function of objective function F, having the form of exponential function, and ΔF is the amendment part.

Slow decay of SIs mainly come from the role of quasi-static wave, when λ tends to infinity. F_{asy} can be extracted by the quasi-near-field conditions.

$$F_{asy}(\mathrm{v}_0)=\lim_{\lambda\to\infty}\frac{k_1^2 v_0-k_0^2 v_1}{k_1^2 v_0+k_0^2 v_1}=\frac{k_1^2-k_0^2}{k_1^2+k_0^2} \quad (5)$$

C. CDEGS simulation

In this paper, we also utilize the commercial software CDEGS to calculate the current distribution in the LPS. In its HIFRQ module, the LPS are modeled by interconnected conductors. The calculation is done in frequency domain. In order to improve calculation accuracy, the define frequencies adopt the calculated values shown in Fig. 1.b but not the recommended values by the FFTSES module. Considering the calculation frequencies, we divided above ground conductor and underground conductor into 1.5m and 0.5m, respectively. The measured injection current is used as a ideal current source. Calculate the system responses by the current source，and use the inverse fast Fourier transform to obtain the transient current distribution of the measurement points.

III. RESULTS

The test house at the ICLRT has approximate dimensions of 10m*7m*6.5m. The LPS configurations of the house tested in 2004 and 2005 are shown in [1]. Lighting current was injected into one of the three air terminals on the roof of the house. In 2004, the LPS has two down conductors, A and B, at the position (SW and NE) corners, each connected to a pair of vertical ground rods, In the middle of the north side of the Test House there was another ground rod C, the power supply system ground rod.

The LPS for the 2005 experiment differed from the LPS installed in 2004. The 2005 setup consisted of two interconnected air terminals, four down conductors, and five ground rods (A, A1, B, B1 for the LPS, and D for the power supply system) interconnected by a buried loop conductor called also a ring electrode or counterpoise.

Improved DCIM is used to calculate magnetic vector potentials of the lightning channel and the connecting wire between the tower and the house and then calculate the induced voltage in the loop formed by the above-ground conductors of LPS. Utilizing the calculated induced voltage as distributed voltage source, we calculate the lightning current concerning electromagnetic coupling between lightning channel and LPS.

The HIFRQ module is based on antenna theory in the frequency domain, which does not take the electromagnetic coupling into account. Superposition of the HIFRQ solution and the coupling lightning current between lightning channel and LPS, we obtain the results with electromagnetic coupling. Fig. 2 shows a comparison of transient current for A in 2004 with and without consideration of the coupling effects. The peak currents are 5.4 kA under consideration coupling effects and 4.3 kA neglecting the coupling effects. Consideration coupling effects is more fit with the measured.

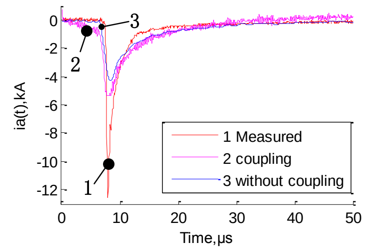


Fig. 2. Comparison of the current for A in 2004 with and without coupling

To verify the results computed by proposed method, a comparison is carried out between the results reported in [3] and those of the new method in Fig. 3.

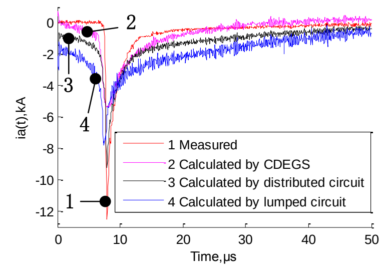


Fig. 3. Calculated and measured current waveforms for A in 2004

IV. CONCLUSION

The distribution of lightning current in the LPS of a residential house is calculated and analyzed. The electromagnetic coupling between lightning channel and the LPS is taken into account. The calculated current distributions in the LPS are compared with the measured ones. Compare with the lumped parameter model, the accuracy of the distributed parameter model improved about 10%.

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