Kasetsart J. (Nat. Sci.) 39 : 319 - 328 (2005)

Lightning Surge Response of Concrete Pole due to Effect of the Electrical Properties of Concrete based on the Electromagnetic Field Method

Samroeng Hintamai and Jamnarn Hokierti

ABSTRACT

Lightning performance of overhead distribution line affects the cost of line construction. For economical insulation coordination in distribution line design, it is necessary to accurately predict the lightning surge overvoltage that occurs in the electric power system. In particularly, tower or pole surge impedance is one of the most important parameters for lightning surge analysis of distribution lines. This paper presents the lightning surge response of reinforced concrete pole due to the electrical properties of concrete based on the electromagnetic field theory, which has never been considered in the previous lightning surge analysis. The electrical properties of concrete were measured over the frequency of range from 100 Hz to 40 MHz during 86 days after pouring. The concrete sample was mixed according to a construction standard of the electrical distribution pole of Provincial Electricity Authority (PEA). The cement/sand/aggregate ratio was about 1:1.5:3 and water/cement ratio was approximately 0.3. It was found that the electrical properties of concrete varied significantly over the frequencies and time after pouring. Therefore, lightning surge response of reinforced concrete pole depended on the electrical properties of concrete. The results showed that surge impedance calculated by the proposed formula agreed well with the other measured value obtained from reduced- scale test.

Key words: concrete pole, electromagnetic field method, electrical properties of concrete, lightning surge response, surge impedance

INTRODUCTION

Thailand is in a tropical zone and has the highest number of thunderstorm days in this zone, about 50-120 days per year. For protection of equipments in the electric power system, a lightning overvoltage is a significant factor. Thus, lightning surge analysis is essential for insulation design of the electric power system. Particularly, tower surge impedance is an important factor in the insulation coordination design for transmission/distribution lines. A number of experimental and theoretical studies on tower surge impedance have been carried out (Motoyama and Matsubara, 2000). However, surge impedance of concrete pole has not been studied enough for lightning surge analysis.

Representative methods to investigate the tower surge characteristics include measurement on real towers, measurement on reduced-scale models, analytical study on simplified geometry

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Received date : 17/09/04 Accepted date : 27/12/04

and numerical analysis based on the electromagnetic theory.

The first theoretical formulation of tower surge impedance was proposed by Jordan (1934). In this formulation, based on Neumann's inductance formula, it was assumed that the current distribution inside the tower was uniform from the tower bottom.

Theoretical formulations of tower surge impedance based on the electromagnetic field theory were proposed by Lundholm *et al.*(1958), Wagner and Hileman(1959), Sargent and Darveniza (1969) and Okumura and Kijima(1985), considering effects of the vector potential generated by the injection current into the tower only. Propagation velocity inside the tower was assumed at the speed of light to the top of the tower. However, the effect of return stroke current was neglected. The tower was approximated as a vertical cylinder having a height equal to the tower, and a radius equal to the mean equivalent radius of the tower. Propagation velocity inside the tower was assumed at the speed of light.

Measurements of the surge impedance of actual transmission towers were reported by Breuer *et al.*(1958) and Caswell *et al.* (1958). In both cases, a reflection method was used, and similar impedance values of 165 ohms were obtained at the tower top. Measured propagation velocity inside the tower was almost the speed of light.

Another experimental value for actual transmission towers was reported by Kawai (1964). He used a direct method to measure tower surge impedance, and obtained an impedance value of 100 ohms at the tower top. His experimental results showed that the tower response to a vertical current is different from the response to a horizontal current. Measured propagation velocity inside the tower was 70–80% of the speed of light.

Scale-model measurements were reported by Chisholm (1983) and Wahab *et al.*(1987). Chisholm used the time-domain reflectometry (TDR) method to measure tower surge impedance. These measurements were performed using both horizontal and vertical current injection. Measured propagation velocity inside the tower was the speed of light. Wahab *et al.*(1987) used the direct method to measure tower surge impedance for various angles of current injection. Measured propagation velocity inside the tower was 80–90% of the speed of light. These results showed that the tower surge impedance was strongly influenced by the angle of current injection.

Field measurements of full-scale tower impedance using the direct method were reported by Ishii *et al.*(1991) and Yamada *et al.*(1995). These measurements were performed using inclined and horizontal current injection. Both papers proposed a surge impedance of the tower based on the Electromagnetic Transient Program(EMTP). Propagation velocity inside the tower was assumed at the speed of light.

Measurements of surge response of a transmission tower to actual lightning were reported by Matsumoto *et al.*(1995), Shinjo *et al.*(1997) and Motoyama *et al.*(1997). All of them estimated the surge impedance of the tower based on the measurements, and proposed a model of the tower based on the EMTP. The results showed that surge response and surge impedance of the tower depended on the lightning discharge path direction.

Theoretical work was reported by Ishii and Baba(1997). They estimated the surge response of a tower by numerical electromagnetic field analysis. The calculated results were compared with field test results (Yamada *et al.*, 1995). The analysis showed that surge response and surge impedance of the tower depended on the arrangement of the current lead.

Theoretical formulation of tower surge impedance based on the electromagnetic field theory was proposed by Motoyama and Matsubara(2000). The analysis showed that the tower surge impedance depended on the direction and velocity of return stroke current.

Recently, theoretical formulation of pole surge impedance of concrete pole based on the electromagnetic field theory, including the effect of direction and velocity of the return stroke current and the electrical properties of concrete, was proposed by Hintamai and Hokierti(2003). The calculated result showed that surge impedance of concrete pole depended on the electrical properties of concrete.

In this paper, a new formula of surge impedance of reinforced concrete pole based on the electromagnetic field theory by taking the effect of the electrical properties of concrete is proposed. The electrical properties of concrete were measured over the frequency range from 100 Hz to 40 MHz during 86 days after pouring.

MATERIALS AND METHODS

1. Model of lightning return stroke current

In this model, as the downward leader nears the earth, an upward leader (or the return stroke) is initiated progresses upwards with a velocity v_R neutralizing the charge lowered by the preceding steeped leader (Chowdhuri *et al.*, 2001). The lightning channel then consists of a vertical column; the lower part, containing current, is rapidly expanding upwards, and the upper part, containing the residual charge of the proceeding steeped leader, is diminishing rapidly, as shown in Figure 1.

The surge impedance of the return stroke is a function of the height and the velocity of the return stroke. However, the conservative assumption that the stroke is a constant current source is almost universally used, i.e., the surge impedance of the stroke is infinite.

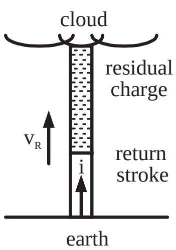


Figure 1 Model of lightning return stroke.

2. Electric field produced by a step current

The geometry adopted for the calculation of electromagnetic filed is shown in Figure 2. This configuration is a crude approximation to the lightning return stroke which travel up with a propagation velocity v_R in lossy dielectric medium from the earth while removing negative charge from the channel previously formed by a downward moving, negative charged, cloud-to-ground leader.

From the electromagnetic field theory, the general solution for electric fields in cylindrical coordination at any point (r,ϕ,z) is defined as (Rubinstein and Uman, 1989),

$$\overline{E} = -\phi - \frac{\partial \overline{A}}{\partial t}, \qquad (1)$$

where

$\overline{E}$: electric field intensity, V/m,

ϕ : scalar electric potential, V and

$\overline{A}$: vector magnetic potential, Wb/m .

From the Lorentz condition,

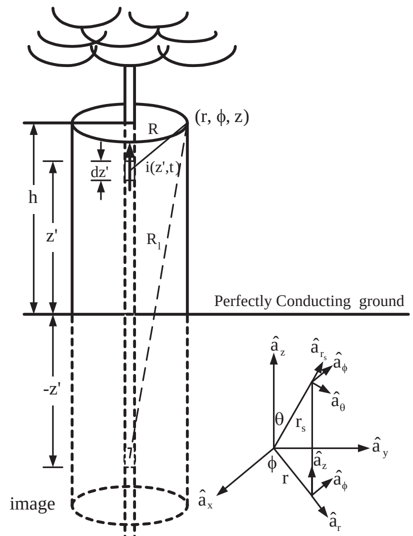


Figure 2 Geometry of a vertical conductor above a perfectly conducting ground.

$$\nabla.\overline{A} + \mu\varepsilon \frac{\partial \phi}{\partial t} = 0 \ , \tag{2}$$

where

μ : permeability of medium, H/m and

ε : complex permittivity of medium, F/m.

It can be shown that the inhomogeneous solutions are

$$\overline{A}(r,t) = \frac{\mu}{4\pi}\int_0^{z'} \frac{I(r',t-R/c)}{R} dz' , \tag{3}$$

$$\phi(r,t) = \frac{1}{4\pi\varepsilon}\int_0^{z'} \frac{\rho(r',t-R/c)}{R} dz' , \tag{4}$$

where

z' : traveling distance of the current, m,

r' : observation coordinates,

r : source coordinates,

$R = |r - r'|$: distance between and , m,

c : propagation velocity of the current in medium, m/s,

ρ : line charge density, C/m and

I : current distribution, A.

The medium of the vertical structure being considered here have conductivity σ, a dielectric constant ε_R and permeability μ. Thus, the complex permittivity is defined as (Plonus, 1988),

$$\varepsilon = \varepsilon_0 \varepsilon_R - j\sigma / \omega . \tag{5}$$

The dipole technique uses infinitesimal time-varying as the source of the electric and magnetic fields. Since the vector potential $\overline{A}_r$ can be found from the current alone, expression ϕ in terms of $\overline{A}$ allows us to write (1) in terms of the current distribution alone. By solving the Lorentz condition, we obtain,

$$\phi(r,t) = -\frac{1}{\mu\varepsilon}\int_0^{t} \nabla.\overline{A} dt + \phi(t=-\infty) . \tag{6}$$

Substituting (6) into (1), we obtain

$$\overline{E}(r,t) = \frac{1}{\mu\varepsilon}\int_0^{t} \nabla\left(\nabla.\overline{A}\right) dt - \frac{\partial \overline{A}}{\partial t} . \tag{7}$$

where $\phi(t=-\infty)$ since the current and charge distributions are zeros for times less than a certain time t_0.

In this analysis, a step current of magnitude I_0 is traveling up in the positive direction inside the concrete pole at velocity v_R. It is convenient to use a mathematical expression describing both the real current distribution and its image at the same time as (Rubinstein and Uman, 1989),

$$i(z',t) = I_0 u\left(t - |z'| / v_R\right) . \tag{8}$$

The function $u(\xi)$ is called the Heaviside function and is defined as,

$$u(\xi) = \begin{cases} 0, & \xi < 0 \\ 1, & \xi \geq 1 \end{cases} .$$

We allow for the presence of the conducting plane by using the method of images. The vector potential $\overline{A}_r$ in cylindrical coordination at any point (r,ϕ, z) can be integrated to yield,

$$\overline{A} = \frac{\mu I_0}{4\pi} \ln \frac{(h-z) + \sqrt{(h-z)^2 + r^2}}{\left(-z + \sqrt{z^2 + r^2}\right)} . \tag{9}$$

The heightcan be found by setting the argument of the Heaviside function to zero. Solving for and inserting into (9), the vector potential $\overline{A}_r$ can be obtained as,

$$\overline{A}_r = \frac{\mu I_0}{4\pi} \ln \frac{(v_R t - z) + \sqrt{(v_R t - z)^2 + r^2}}{\left(-z + \sqrt{z^2 + r^2}\right)} . \tag{10}$$

Meanwhile, we can calculate vector potential at the same point from the image channel. Since to change the actual channel to the image channel all we can change z to $-z$, it is readily seen that

$$\overline{A}_i = \frac{\mu I_0}{4\pi} \ln \frac{(v_R t + z) + \sqrt{(v_R t + z)^2 + r^2}}{\left(z + \sqrt{z^2 + r^2}\right)} . \tag{11}$$

The sign of the vector potential from image is the same as from the source because the directions of current are the same for both. The total vector potential is then given by,

$$\overline{A}(z) = \overline{A}_r(z) + \overline{A}_i(-z). \quad (12)$$

Substituting (12) into (7), we obtain the total electric field intensity in cylindrical coordination at any (r,ϕ, z) point as,

$$\overline{E}_z = -\frac{60I_0}{\sqrt{\varepsilon_R - j\sigma / \varepsilon_0\omega}}\left(\frac{1}{\sqrt{z^2 + r^2}}\right). \quad (13)$$

3. Surge impedance of concrete pole

3.1 Single conductor model

If the lightning stroke starts from the top of the pole at, $t=0$ the pole top voltage V_{top} is obtained by,

$$V_{top} = -\int_0^h \overline{E}_z dz \, . \quad (14)$$

For $0 \le t < (r/c)$, the wave front of the electromagnetic wave does not pass the point. Therefore,

$$V_{top} = 0 \, . \quad (15)$$

For $(r/c) \le t < (h/v_R + r/c)$, the wave front of electromagnetic wave passes through the point (r,ϕ,z). Therefore,

$$V_{top} = \frac{60I_0}{\sqrt{\varepsilon_R - j\sigma / \varepsilon_0\omega}} \ln\left(\frac{h + \sqrt{h^2 + r^2}}{r}\right) . \quad (16)$$

For, $t > h/v_R + r/c$ the electromagnetic wave reflected on the ground surface reaches the pole top. Therefore,

$$V_{top}(t) = V_{top}\left(h / v_R + r / c\right) . \quad (17)$$

Since the voltage V_{top} is produced by the vertical return stroke current I_0, the pole surge impedance Z_{pole} is defined as,

$$Z_{pole} = \frac{V_{top}}{I_0} = \begin{cases} 0, & 0 \le t < (r/c) \\ \dfrac{60}{\sqrt{\varepsilon_R - j\sigma / \varepsilon_0\omega}} ln\left(\dfrac{h + \sqrt{h^2 + r^2}}{r}\right), & (r/c) \le t < \left(h / v_R + r / c\right) \\ V_{top}\left(h / v_R + r / c\right), & t < \left(h / v_R + r / c\right) \end{cases} \quad (18)$$

Finally, the surge impedance of concrete pole Z_{pole} can be obtained as,

$$Z_{pole} = \frac{60}{\sqrt{\varepsilon_R - j\sigma / \varepsilon_0\omega}} ln\left(\frac{h + \sqrt{h^2 + r^2}}{r}\right), \quad (19)$$

where h is the height of the pole.

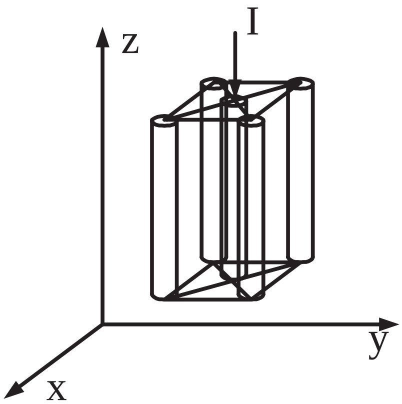
3.2 Multiconductor model

An actual concrete pole is composed of multiconductor as shown in Figure 3. The five conductors being short-circuited at its boundary (top and/or bottom), the total impedance seen from the top is given considering the mutual impedances between the conductors by

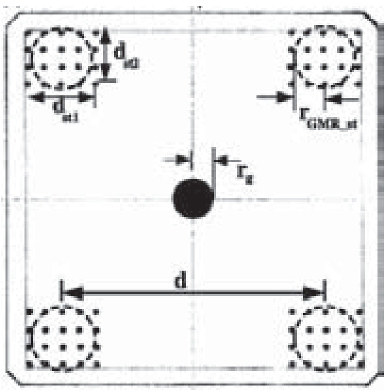
$$Z_{pole} = \left(Z_{11} + 2Z_{12} + Z_{13} + Z_{15}\right) = \frac{60}{\sqrt{(\varepsilon_r - j\sigma / \varepsilon_0\omega)}} \frac{ln\left(\dfrac{d}{\sqrt{2r_g}}\right) ln\left(\dfrac{d}{4\sqrt{2}r_{GMR,st}}\right)}{ln\left(\dfrac{d^5}{16\sqrt{2}r_{GMR,st}r_g^4}\right)} + \frac{60}{\sqrt{(\varepsilon_r - j\sigma / \varepsilon_0\omega)}} ln\left(\frac{2\sqrt{2}h}{d}\right) \quad (21)$$

where $r_{GMR,st} = \sqrt[4]{r_{st} d_{st_1} d_{st_2} \sqrt{\left(d_{st_1}^2 + d_{st_2}^2\right)}}$.

If it is tedious to calculate each component of the above equation, the total surge impedance is easily evaluated as the impedance of an equivalent circular single conductor with the following geometrical mean radius



a) structure inside of concrete pole



b) cross section area

Figure 3 Multiconductor model of concrete pole.

$$Z_{pole} = \frac{60}{\sqrt{\varepsilon_R - j\sigma / \varepsilon_0 \omega}} ln\left(\frac{h + \sqrt{h^2 + R_{GMR}^2}}{R_{GMR}}\right), \tag{22}$$

where $R_{GMR} = \sqrt[5]{(r_g)^{1/5} (r_{GMR,st})^{1/5} d^4}$.

RESULTS AND DISCUSSION

1. Electrical properties of concrete

The electrical properties of concrete were measured over the frequency range from 100 Hz to 40 MHz during 86 days after pouring, using Impedance/Gain-Phase Analyzer Hewlett Packard 4164A with an accuracy of 0.17 percent as shown in Figure 3. The concrete sample was formed by placing aluminum plate electrode about 1 cm in thickness. The cement/sand/aggregate ratio in preparing the concrete specimen was about 1:1.5:3 and the water/cement ratio was near 0.3. Capacitance and dissipation factor were measured by impedance analyzer. Dielectric constant and electrical conductivity were calculated from the measured values. Change of the dielectric constant and the electrical conductivity with the curing time and frequency are shown in Figures 5 and 6.

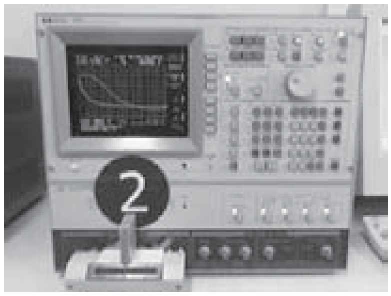


Figure 4 Measurement of the electrical properties of concrete.

In the first 3 days, dielectric constant and electrical conductivity decreased rapidly. After 10 days, their changes become very slow. These changes show good consistency with the chemical change and water content in the hardening period of concrete. Therefore, frequency of lightning current of the first strokes is 25 kHz (10/350 µs), dielectric constant of concrete is about 16 and electrical conductivity is about 0.01 mS/m. Another frequency of lightning current of the subsequent strokes is 1 MHz (0.25/100 µs), dielectric constant of concrete is about 8 and electrical conductivity is about 0.122 mS/m.

2. Propagation velocity of wave

The propagation velocity of return stroke current inside a medium of complex permittivity ε is varied inversely to the square root of the complex permittivity as (Morshedy, 2000),

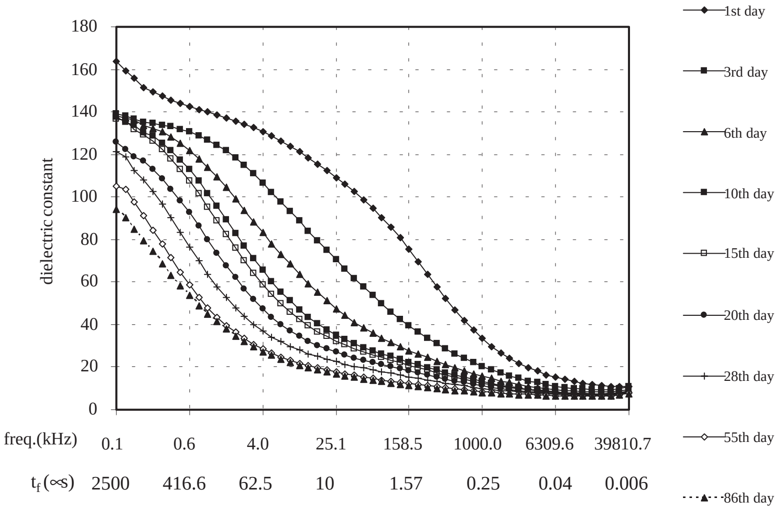


Figure 5 Change of dielectric constant of concrete.

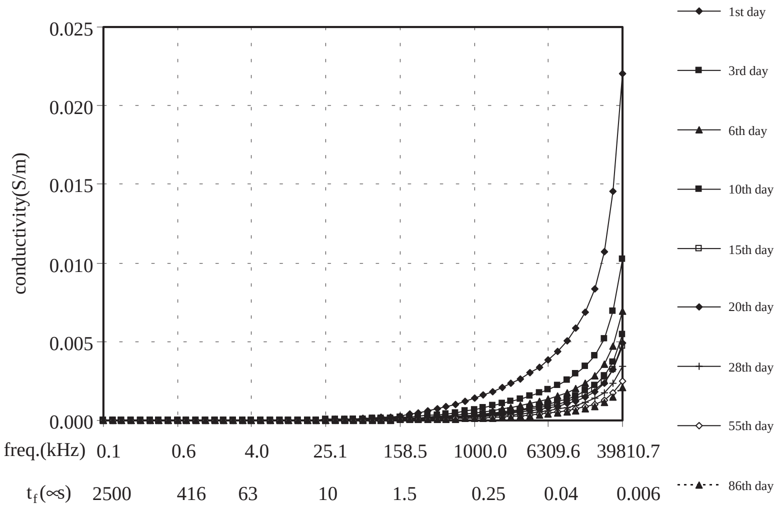


Figure 6 Change of electrical conductivity of concrete.

$$velocity = \frac{3 \times 10^8}{\sqrt{\varepsilon_R - j\sigma / \varepsilon_0 \omega}}. \qquad (23)$$

The propagation velocity of return stroke current inside the concrete pole is shown in Figure 7.

In Figure 7, the propagation velocity of wave inside the concrete pole is about 70 to 103.6 m/μs as the frequency of lightning current is between 25 kHz to 1 MHz.

3. Comparison between calculated result and measured result

To clarify the effectiveness of the proposed formula, we show the comparison of surge impedance of reinforced concrete pole calculated by the proposed formula with the measured result (Yamamoto *et al.*, 1997). The surge impedance of reinforced concrete pole was measured by scale model technique. The height of reinforced concrete pole is 14 m and a radius of 0.377 m. The hollow

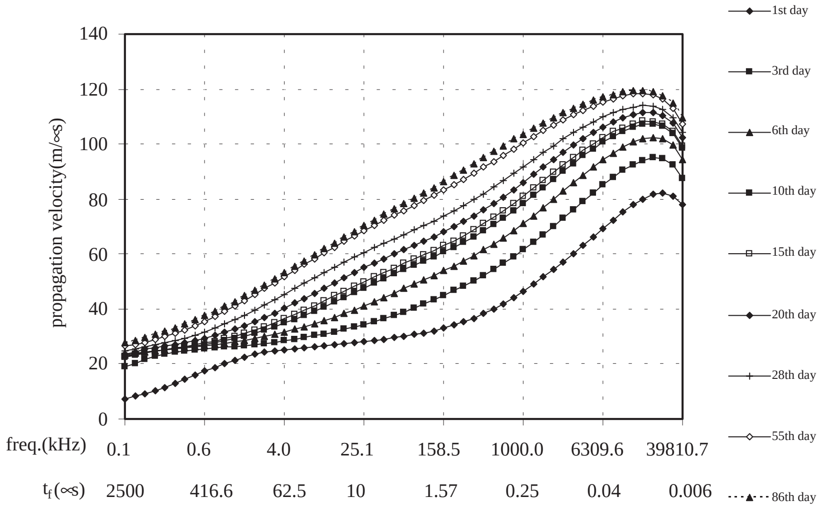


Figure 7 Propagation velocity of return stroke current inside the concrete pole.

steel reinforced concrete pole was composed of two parts; iron cage and concrete part of about 2 mm in thickness. The surge impedance was measured about 242 ohms, whereas calculated result from this configuration by the proposed formula is about 258 ohms. Therefore, it showed that calculated value is different from measured value about 6.8%.

4. Model of concrete pole

This study deals with 22 m in height of concrete pole that imbedded a grounding lead wire of 35 mm^2 at the center of the pole from top to bottom and supplemental steel reinforced at square inside of solid taper pole, as shown in Figure 8.

5. Surge impedance of concrete pole

Figure 9 shows the calculation of surge impedance of concrete pole by equation (22) due to the effect of the electrical properties of concrete. The frequency of lightning current is between 25 kHz to 1 MHz, surge impedance of concrete pole is about 80 to 119 ohms.

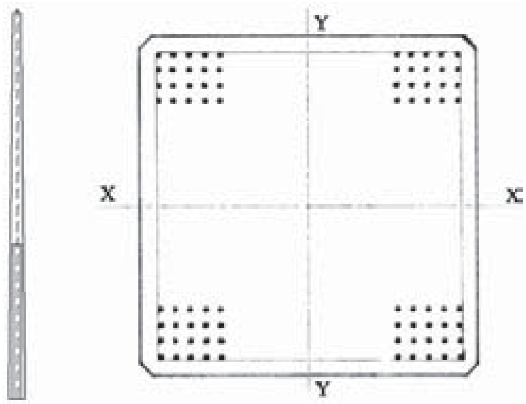


Figure 8 Configuration of the reinforced concrete pole.

CONCLUSIONS

In this paper, the formulation of lightning surge response of reinforced concrete pole based on the electromagnetic field by taking the effect of the electrical properties of concrete was obtained. The results showed that surge impedance of reinforce concrete pole depended on the geometry of pole, the dielectric constant and the electrical conductivity of concrete.

ACKNOWLEDGEMENTS

The authors wish to thank the Electrical Properties Measurement Laboratory of the National Metal and Material Technology Center for service

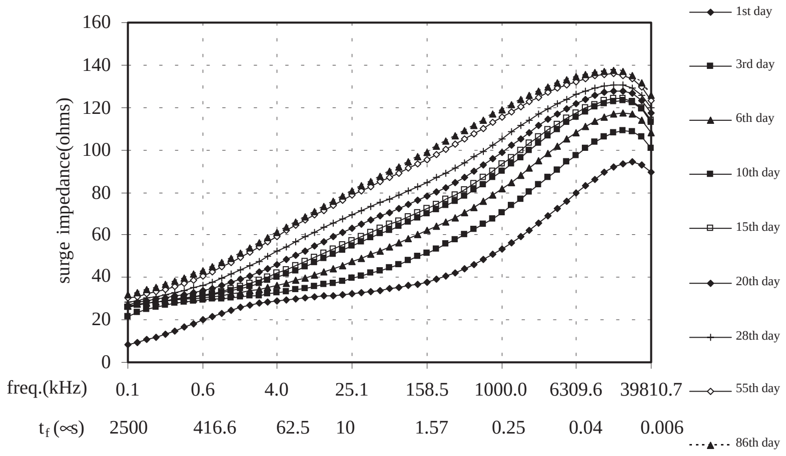


Figure 9 Surge impedance of concrete pole.

of the concrete electrical properties of measurement.

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