CALCULATION OF LIGHTNING TRANSIENT RESPONSES IN GROUNDING SYSTEMS

Weidong Shi [1] , Yu Yin [1] , Xiaoqing Zhang [2]

[1] China Electric Power Research Institute, Beijing 100192, China
[2] Beijing Jiaotong University, Beijing 100086, China
*Email: < wdshi@epri.sgcc.com.cn>

Abstract: This paper proposes an efficient method for calculating the lightning transient responses in grounding systems. The nonlinear relationship is introduced to characterize the electric field and current density in the ionization zone surrounding the grounding branch. The equivalent radius of the grounding branch is evaluated according to the nonlinear relationship. The analytical formulas are given for estimation of the circuit parameters of the grounding branch by using the equivalent radius. The grounding branch segments are represented by the π-type circuit units. Based on the π-type circuit units, the equivalent circuit model is set up for the grounding systems. Then, the validity of the proposed method is verified by comparing the calculated result with the measured one.

1 INTRODUCTION

The transient performance of grounding systems is most important for lightning protection design of substations and transmission lines. A correct choice of protective measurements against lightning overvoltage depends on the knowledge of the transient behaviour of grounding systems during dissipation of lightning current into the soil. In order to perform transient analysis of grounding systems, a few methods have been presented by different researchers [1-3]. However, their modelling for the soil ionization phenomenon is still a problem. These previous methods usually utilized a linear relationship to characterize the electric field and current density in the ionization zone around the grounding branch. In fact, the relationship between the electric field and current density in the ionization zone has a pronounced nonlinearity according to the experimental investigation [4]. The nonlinear relationship should be taken into account for accurately analyzing lightning transient behaviour of grounding systems. Therefore, an efficient method is proposed in this paper for calculating the transient responses in the grounding system excited by a lightning current. The proposed method uses a nonlinear relationship to describe the electric field and current density in the ionization zone instead of the previous linear one. The border of the ionization zone is determined by the soil critical electric field intensity. The ionization zone is equivalently considered as an increase in the radius of the grounding branch and an equivalent radius is introduced for this purpose. In terms of the boundary potential condition of the ionization zone, the simplified procedure is given to estimate the equivalent radius. After obtaining the equivalent radius, the resistance, inductance and capacitance parameters (*RLC*) can be calculated for the grounding branch by substituting its equivalent radius into the respective parameter formula. In consideration of the propagation phenomenon, each grounding branch of the grounding system is subdivided into a suitable number of segments. The length of each segment is assumed to be less than or equal to one tenth of the equivalent wavelength of the injected lightning current. Accordingly, the grounding system is divided into a series of segments. Each segment is replaced by a π type circuit unit constituted by transverse resistance-inductance (*R*-*L*) and longitudinal conductance-capacitance (G-*C*). As a result, the grounding system is converted into an equivalent circuit constituted by a series of the π type circuit units. Once the equivalent circuit is formed, the lightning transient responses in the grounding system can be calculated by circuit analysis technique. In confirm of the validity of the proposed method, the calculated result is compared with the measured one and a better agreement appears between them.

2 CIRCUIT MODELING OF GROUNDING BRANCHES

The grounding system is illustrated as Figure 1(a). For each grounding branch, as shown in Figure 1(b), its circuit parameters are given under the condition of soil unionization [5].

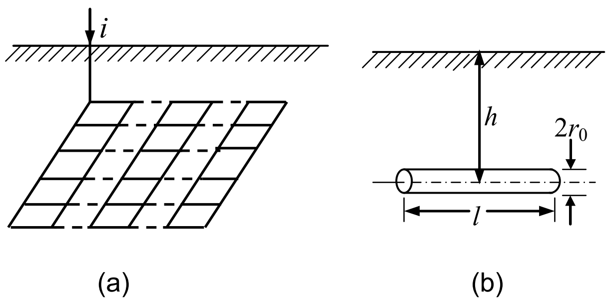

Figure 1 Grounding system and its branch

$$L_0 = \frac{\mu_0}{2\pi}\left[\ln\frac{2l}{\sqrt{2hr_0}} - 1\right]$$

$$C_0 = \frac{2\pi\varepsilon}{\ln\frac{2l}{\sqrt{2hr_0}} - 1} \tag{1}$$

$$G_0 = \frac{\pi}{\rho\left(\ln\frac{2l}{\sqrt{2hr_0}} - 1\right)}$$

where: L_0= Inductance per unit length (H/m)
C_0= Capacitance per unit length (F/m)
G_0=Conductance per unit length (S/m)

In order to obtain an equivalent circuit for the grounding system, each grounding branch is divided in a number of segments. The length of each segment Δl is less than 1/10 lightning current wavelength corresponding to the maximum frequency likely to affect the grounding system transient [6]. A π-type circuit unit is employed to represent the segment, as shown in Figure 2. As a result, the complete grounding system can be converted into an equivalent circuit formed by *RGLC*. The lightning current is injected to a node

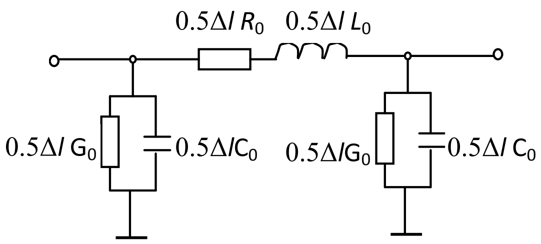

Figure 2 π-type circuit unit

of the equivalent circuit and the transient responses can be calculated by circuit analytical method.

3 SIMPLIFIED DESCRIPTION OF SOIL IONIZATION

When a low current *i* with low frequency flows through a grounding branch and insufficient to initiate soil breakdown, the relationship between the electric field and current density in the soil is linear, i.e.

$$E = \rho J \tag{2}$$

where: *E*=Electric field intensity
J= Current density

However, when a high impulse current, representative of lightning, flows through the grounding branch and dissipates into the soil, the soil breakdown will occur. This process is illustrated in Figure 3. As the current increases, streamers are developed and in turn arcs are generated. Within the streamer and arc zones, the soil resistivity decreases from its original value to a limit of approaching conductor. In addition, there is also a semiconductive zone between the streamer zone and the constant resistivity zone. For simplicity,

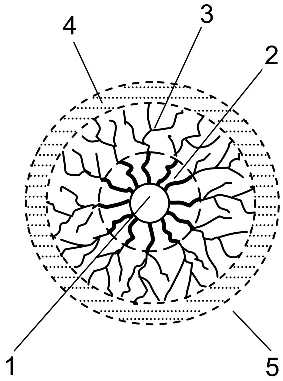

Figure 3: Impulse breakdown of soil surrounding a grounding electrode. 1—grouding electrode; 2—arc zone; 3—streamer zone; 4—semiconductive zone; 5—constant resistivity zone.

this process can be described by a simplified model, as shown in Figure 4 [6]. In the simplified

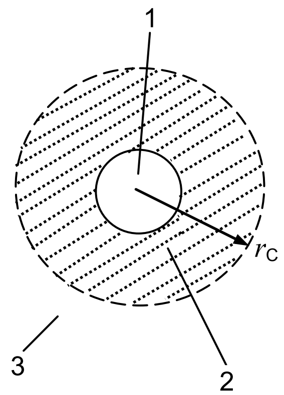

Figure 4: Simplified model of ionization zone. 1—grouding electrode; 2—ionization zone; 3—constant resistivity zone

model, the semiconductive zone is neglected since it is small, while the streamer and arc zones are modelled as an ionization zone. The border of the ionization zone is delimited by the critical electric field intensity E_C of soil breakdown. A nonlinear relationship is introduced to characterize the electric field and current density in the ionization zone. The nonlinear relationship is expressed as follows

$$E = a\,J^b \tag{3}$$

where: *a* and *b* are constants that were given for typical kinds of soils in [4].

For a horizontal grounding branch segment with a length of Δl, as shown in Figure 5, its current density can be approximately expressed as [3]

$$J = \frac{I}{2\pi r \Delta l} \tag{4}$$

where: I = current peak
Substituting eqn. 4 into eqn. 3, the electric field

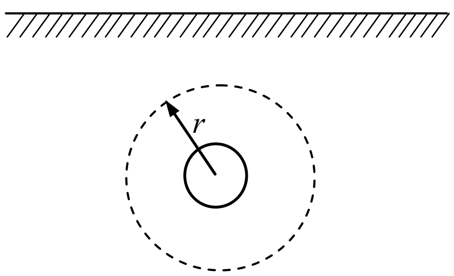

Figure 5: Current dissipation surface of a horizontal grounding branch

intensity is written as

$$E = a\left(\frac{I}{2\pi r \Delta l}\right)^{b} \tag{5}$$

On the border of the ionization zone, E takes the critical value E_C

$$E\big|_{r=r_H} = E_C \tag{6}$$

Thus, the boundary radius of the ionization zone can be derived from eqns. 5 and 6

$$r_H = \frac{I}{2\pi\Delta l\left(\frac{E_C}{a}\right)^{\frac{1}{b}}} \tag{7}$$

If the boundary radius r_H satisfies

$$r_H \geq \frac{h}{\sqrt{3}} \tag{8}$$

The effective buried depth of the grounding branch, as illustrated in Figure 6, is estimated from the following expression [6]

$$h_{ca} = \sqrt{r_H^2 + h^2} \tag{9}$$

where: h= buried depth of the grounding branch.

When r_H is small and does not satisfy inequality 8, the difference h_{ca}-h can neglected and eqn. 9 takes the following form

$$h_{ca} \approx h \tag{10}$$

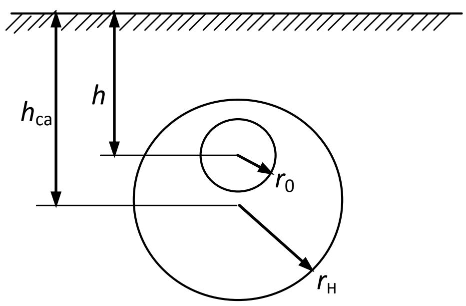

Figure 6: The effective buried depth

The soil breakdown is basically equivalent to an increase in the dimension of the grounding branch. This increase can be represented by an equivalent radius r_e of the grounding branch, as shown in Figure 7. The voltage between the grounding

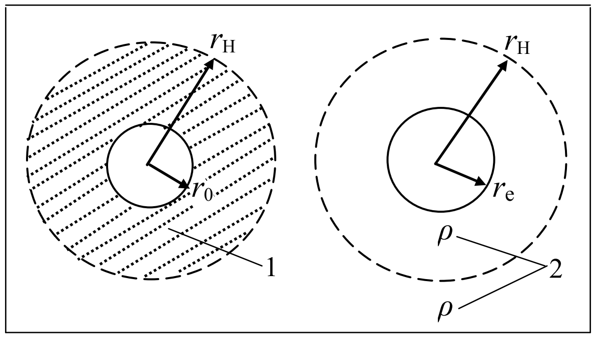

Figure 7: Sketch of the effective radius. 1—ionization zone, 2—constant resistivity zone

branch segment and the border of the ionization is

$$U_{0H} = \int_{r_0}^{r_H} a\left(\frac{I}{2\pi r \Delta l}\right)^{b} dr = \left(\frac{I}{2\pi\Delta l}\right)^{b} D \tag{11}$$

where D is

$$D = \frac{a}{1-b}\left(r_H^{1-b} - r_0^{1-b}\right)$$

The voltage between the equivalent grounding branch segment and the equipotential surface with radius r_H is

$$U_e = \int_{r_e}^{r_H} \frac{\rho I}{2\pi\Delta l\, r} dr = \frac{\rho I}{2\pi\Delta l}\ln\frac{r_H}{r_e} \tag{12}$$

Because U_{oH} and U_e must be equal, the equivalent radius r_e can be determined by eqns. 11 and 12

$$r_e = \frac{r_H}{e^{\left(\frac{I}{2\pi\Delta l}\right)^{b-1}\frac{D}{\rho}}} \tag{13}$$

By replacing r_0 with r_e in eqn. 1, the circuit parameters including soil breakdown can be calculated. Therefore, the effect of soil breakdown can be taken into account in transient calculation of grounding systems in a nonlinear manner.

4 NUMERICAL EXAMPLE

The grounding system is shown in Figure 8 , where h=1m, ρ=359Ω•m, $E_c = 241\rho^{0.215}$ [8], *a*=3094.6 and *b*=0.51 [4]. The impulse current *i* is injected into the central node A of the grounding system, whose waveform is shown in Figure 9(a). The transient potential u_A at the central node A is calculated by the proposed method, and shown in Figure 9(b), where the measured result [6] is also given for comparison. It can be seen from Figure 9(b) that a better agreement appears between calculated and measured results. Thus , the validity of the proposed method is confirmed.

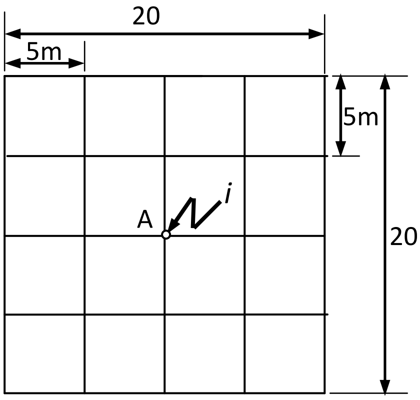

Figure 8: The grounding system structure

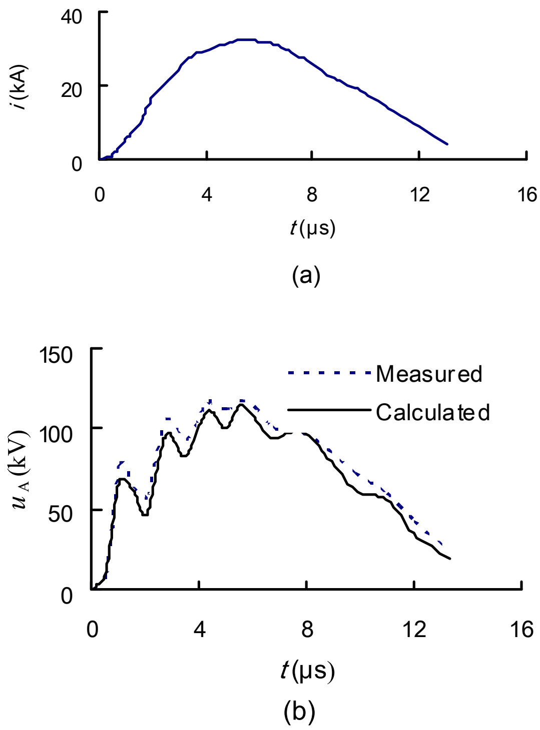

Figure 9: Current and potential waveforms at node A

5 CONCLUSION

A novel method for calculating the lightning transient response in grounding systems has been proposed in this paper. The analytical formulas are given for estimation of the electrical parameters of grounding branches and the π-type circuits are used to represent the grounding branch segments. In order to take account of the soil breakdown influence on the lightning transient response, the soil breakdown is simulated as a simplified ionization zone around the grounding branch. The equivalent radius of the grounding branch can be determined in terms of the critical electric field intensity value of soil breakdown, which is then applied to the lightning transient calculation. Also, the proposed method has been validated by comparing the calculated result with the measured one.

6 REFERENCES

[1] A. Geri, “Behaviour of grounding system exited by high impulse currents: the model and its validation”, IEEE T PWRD, Vol.17, No. 3, pp. 1008-1017,1999

[2] L. Huang, G K. Donald, “Modelling of grounding grid and metallic structure currents in high voltage a. c. substations for computation of electromagnetic fields”, Electric Power System Research, Vol. 59, pp.31-38, 2001

[3] R.Velazquez and D. Mukhedkar, “Analytical modelling of grounding electrodes transient behavior,” IEEE T PAS, Vol.103, No.4, pp.1314–1322, 1984

[4] A. Z. Annenkov, “The Volt-Ampere characteristics of soil under lightning surge currents”, Electrichestvo, No. 2, pp.57–60, 1986

[5] R. Velazquez, D. Mukhedkar, ”Analytical modeling of grounding electrodes transient behavior”, IEEE T PAS, Vol. 103, No. 6, pp.1314- 1322

[6] Z. X. Qin, M. Lan, “Lightning Transient Response on Grounding Grids”, High Voltage Technique, Vol. 28, No.10, pp.1-5, 2003

[7] Z. Stojković, “The soil ionization influence on lightning performance of transmission lines”, Electrical Engineering, Vol. 82, pp.49–58, 1999

[8] E. E. Oettle, “A new general estimation curve for predicting the impulse impedance of concentrated earth electrodes”, IEEE T PWRD, Vol.3, No.4, pp.2020-2029, 1988