Research on Electromagnetic Disturbance Intensity Distribution of Substation Based on Traveling Wave Antenna Theory

Ninghui He, Xutao Wu, Yifan Lang, Zijian Huang, Yaowen Wen, and Yangchun Cheng

Abstract The electromagnetic environment in AIS substations is complex and variable, the operating arc of isolation switch or lightning intrusion wave can generate extremely strong transient electromagnetic harassment, which seriously affects the performance of sensors. Therefore, analyzing the electromagnetic environment of substations is necessary to improve their anti-interference performance and ensure the safe and reliable operation of the power system. Firstly, based on the theory of traveling wave antenna, the theory of electromagnetic wave refraction and reflection, and the superposition principle, a calculation model of electromagnetic field radiated by transient current waves in complex high-voltage networks considering long conductors and metal shells of equipment is established in this paper; Then a typical 110 kV AIS substation model is simulated by the electromagnetic wave simulation software, and the electromagnetic field distribution at the installation location of common transformer equipment live detection and online monitoring sensors in the substation is analyzed under different transient disturbance scenarios. Based on the above research, the electromagnetic compatibility reliability test parameters of sensors have been clarified, and the installation method of sensors has been optimized to improve the anti-electromagnetic interference ability of sensors in the substation.

Keywords Traveling wave antenna theory · Electromagnetic field · Thunder wave · Switching impulse

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1 Introduction

The extremely strong transient electromagnetic interference in substations poses a huge threat to state sensing sensors, especially low-power smart sensors. Taking the electromagnetic interference generated by the action arc of the isolation switch as an example: during the operation of the high-voltage isolation switch, there will be dozens or even hundreds of times of arc extinguishing and burning at the switch fracture. Due to the influence of electromagnetic interference during the switch operation process, the electromagnetic working environment is harsh, and the reliability and anti-interference issues of the protection device become more prominent.

The Electric Power Research Institute of the United States has developed a measurement system for the electromagnetic environment of substations through on-site measurements of multiple substations, and obtained a large amount of electromagnetic steady-state and transient disturbance data inside the substations [1, 2]. Russell et al. [3] provided transient electromagnetic disturbance levels and obtained electromagnetic disturbance waveforms for a large number of AIS and GIS substations with isolation switch operations at 500 kV and below through on-site testing. Rao et al. [4, 5] studied the electromagnetic interference phenomenon during switch operation in GIS, and measured the induced current, voltage, and transient electric and magnetic fields generated by secondary equipment during switch operation in GIS substations with voltage levels of 230 and 500 kV. Zhang et al. [6–9] measured and analyzed the transient electromagnetic interference caused by switch operation in substations. The Electromagnetic Compatibility Laboratory of North China Electric Power University measured and analyzed the electromagnetic interference caused by the switch operation of smart component current transformer ports in 500 kV GIS [10]. Kong et al. [11] studied the transient electric field measurement method for switching operation of DC circuit breakers. Rao et al. [12] measured the power frequency electromagnetic field in 220 and 500 kV substations.

Based on the research mentioned above, this article conducts a theoretical analysis of the propagation of disturbance sources on long wires based on the theory of traveling wave antennas. And the electromagnetic wave refraction and reflection theory was used to explain the shielding effect of transformer and other substation devices on electromagnetic waves. On this basis, the distribution of electromagnetic disturbance intensity in the substation under the action of disconnector operation wave and lightning intrusion wave is analyzed through a typical 110 kV substation model,, and the electromagnetic intensity at the typical location where the sensor is installed is emphatically analyzed. The results obtained can lay a solid foundation for further research on the rational electromagnetic protection design of smart sensing equipment and the development of relevant detection standards.

2 Methods

2.1 Traveling Wave Antenna Theory

When a long wire is terminated with a matching resistor R_L, there are no reflected waves, and the current on the wire is a traveling wave. To simplify the analysis and ignore the influence of the bottom, the radiation of the vertical section of the wire and the attenuation of the current along the line are ignored. The simplified structure and coordinates of the long wire are shown in Fig. 1.

Assuming that the phase constant of the traveling wave propagation along the wire is equal to the phase constant k of the wave in free space, the current along the long wire can be expressed as:

$$I(z) = I_0 e^{-jkz} \tag{1}$$

According to the superposition principle, the far field of a long wire can be obtained by superposition of the far field of each current element on it. According to the basic principles of microwave science, when $kr > > 1$ or $r > > \lambda$ The far field of the current source I (z) dz at z on the traveling wave length wire is as follows:

$$\mathrm{d}E_\theta = \mathrm{j}\frac{60\pi I_0}{\lambda r} sin\theta e^{-\mathrm{j}kz} e^{-\mathrm{j}k(r-z\cos\theta)}\mathrm{d}z \tag{2}$$

where r is the distance from the source point to the field point at z = 0.

The far-field of a row wavelength wire with a length of l is as follows:

$$\begin{aligned} E_\theta &= \int_0^l \mathrm{d}E_\theta = \mathrm{j}\frac{60\pi I_0}{\lambda r} sin\theta e^{-\mathrm{j}kr} \int_0^l e^{-\mathrm{j}kz(1-\cos\theta)}\mathrm{d}z \\ &= \frac{60 I_0}{r} e^{-\mathrm{j}kr} \frac{sin\theta}{1-\cos\theta} \sin\left[\frac{kl}{2}(1-\cos\theta)\right] e^{-\mathrm{j}\frac{kl}{2}(1-\cos\theta)} \end{aligned} \tag{3}$$

The direction function is as follows:

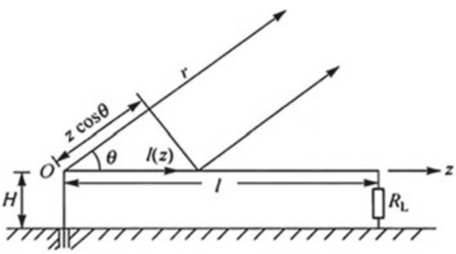


Fig. 1 Schematic diagram of line wavelength wire antenna

$$f(\theta) = \frac{sin\theta}{1 - \cos\theta} \sin\left[\frac{kl}{2}(1 - \cos\theta)\right] = \cot\frac{\theta}{2} \sin\left[\frac{kl}{2}(1 - \cos\theta)\right] \quad (4)$$

2.2 Theory of Electromagnetic Wave Refraction and Diffraction

Reflection of electromagnetic waves on the surface of conductors. Electromagnetic waves undergo reflection and refraction at the interface of different media. The incident, reflected, and transmitted waves at the interface are related to the magnetic permeability of materials on both sides of the interface μ and dielectric constant ε. Any point source can be developed as an integral superposition of *TE* type and *TM* type z-direction plane wave spectrum, and the propagation of plane wave in plane layered composite media can be described by reflection coefficient and transmission coefficient. Theoretical analysis has shown that both TE and TM waves will undergo total reflection on the surface of an ideal conductor. Thus, the surface of the transformer oil tank forms a reflection wall for external electromagnetic waves.

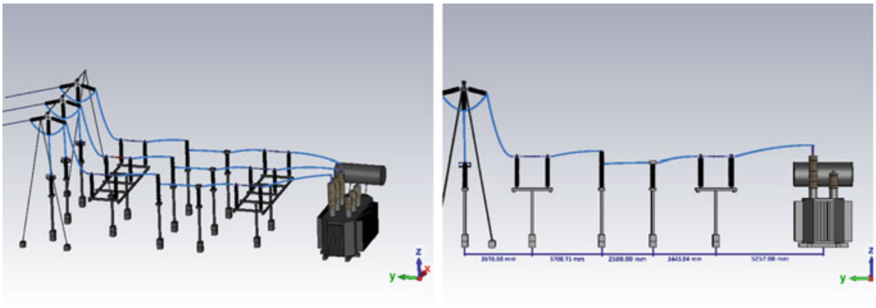
Diffraction of electromagnetic waves on the surface of conductors. Diffraction of waves refers to the phenomenon of waves encountering obstacles, bypassing the edges of obstacles and entering geometric shadow areas during propagation. When geometrical optics rays encounter the discontinuity of an object, diffraction will occur. Keller proposed a new method for approximate calculation of high-frequency electromagnetic fields in 1957. He introduced a new diffracted ray to eliminate the discontinuity of the field on the shadow boundary of geometrical optics rays, and properly corrected the field in the shadow area, which is called geometric diffraction theory.

3 Simulation Modeling and Result Analysis

3.1 Modeling

A typical 110kV AIS substation was established by electromagnetic field simulation software, which includes the most basic components, such as lightning arresters, isolation switches, circuit breakers, voltage transformers, and transformers. All components are arranged with reference to ordinary AIS substations. The substation model used for simulation calculation is shown in Fig. 2.

Disturbance scenario of isolation switch operation wave. A single-phase (intermediate phase) standard operating wave of 250/2500 μs was applied to the isolation switch on the side away from the transformer. According to the requirements of



(a) Aerial view of the model. (b) Front view of the model.

Fig. 2 AIS substation model schematic diagram

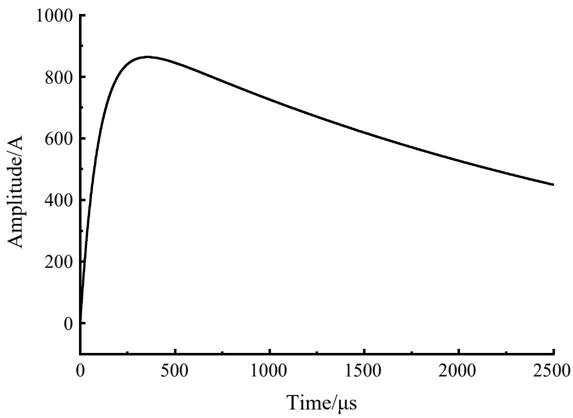
the Electrical Equipment Manual for Electrical Engineering, the rated current of the isolation switch is around 600–1000 A. Therefore, a current wave with an amplitude of 1000 A is selected as the operating wave to simulate the electromagnetic interference experienced by the substation when the isolation switch operates. The waveform of the disturbance source is shown in Fig. 3.

The operation of isolation switches often accompanies the generation of arcs. In this simulation model, the commonly used arc model is used for the arc resistance. Its expression is as follows:

$$r(t) = R_0 \cdot e^{-t/\tau} + R_1 \tag{5}$$

where $R_0 \cdot e^{-t/\tau}$ is the arc resistance during the initial stage of discharge, R_0 is generally taken as 10^{12} Ω, and τ is generally taken as 1ns. R_1 is the arc resistance during the steady-state arcing stage, usually taken as 2–5 Ω.

Fig. 3 Waveform of isolation switch operation wave



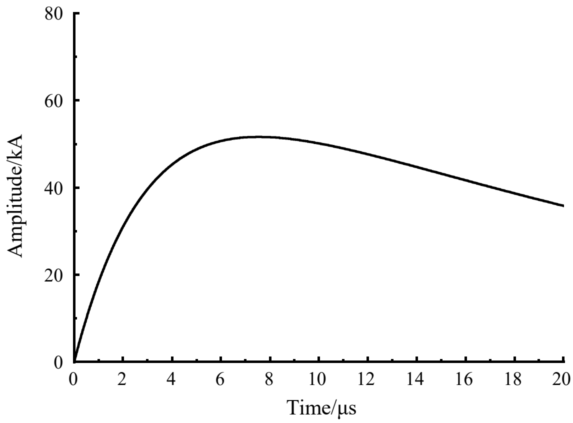


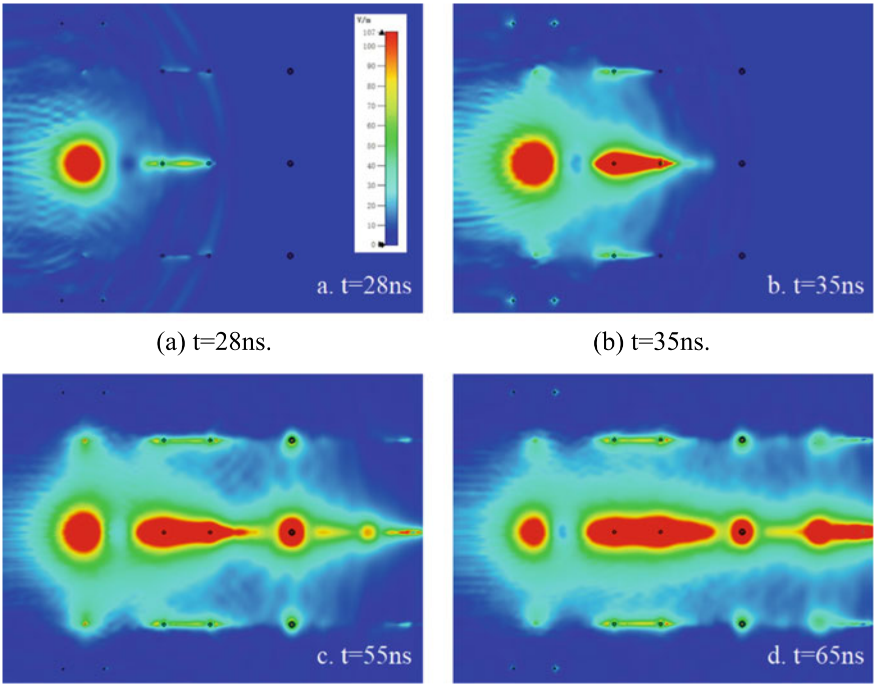
Fig. 4 Waveform of lightning wave

Disturbance scenario of lightning intrusion waves. Apply common lightning current wave 8/20 μs at the incoming line of the substation. The current amplitude value is 80 kA. The waveform of the disturbance source is shown in Fig. 4.

3.2 Propagation of Electromagnetic Waves in Substations Under the Influence of Disturbance Sources

The coupling effect of parallel long wires. When a disturbance source is coupled to a wire, the electromagnetic radiation field generated by the traveling waves on the wire overlaps with the original electromagnetic radiation field, causing changes to the original electromagnetic radiation field. The electromagnetic field at some positions is strengthened by the conduction of traveling waves on long wires. As shown in Fig. 5, the coupling effect of parallel long wires on disturbance sources.

Shielding of electromagnetic radiation by metal enclosures of electrical equipment. According to the analysis above, the metal casing of large electrical equipment such as transformers has a shielding effect. Figure 6 shows the shielding effect of the transformer on the disturbance source.



(a) t=28ns. (b) t=35ns.

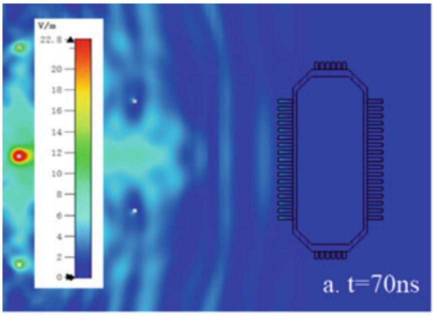
(c) t=55ns. (d) t=65ns.

Fig. 5 Coupling of Parallel Long Wires to Disturbance Sources

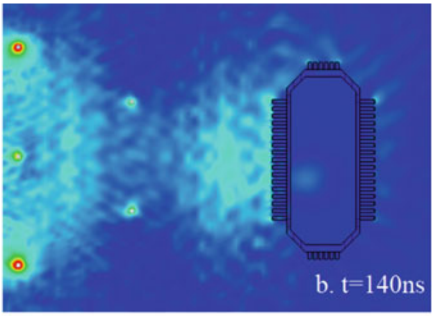
3.3 Electromagnetic Disturbance Intensity Distribution

Electromagnetic disturbance intensity at the transformer bushing. In the research of transformer live detection, many sensors are often installed at the transformer bushing, thus it is necessary to analyze the electromagnetic interference intensity at the transformer bushing. Figure 7 shows the electromagnetic disturbance intensity at the transformer bushing.

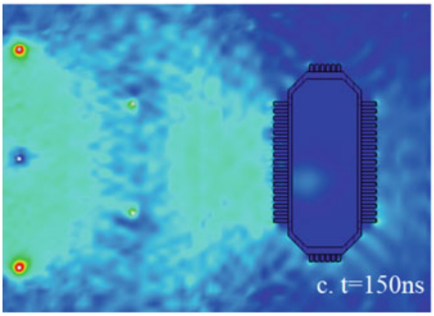
Electromagnetic disturbance intensity around the transformer. Various detection devices are often installed around transformers, analyzing the electromagnetic interference intensity around transformers can help with the scientific arrangement of detection devices. Figure 8 shows the electromagnetic disturbance intensity around the transformer.



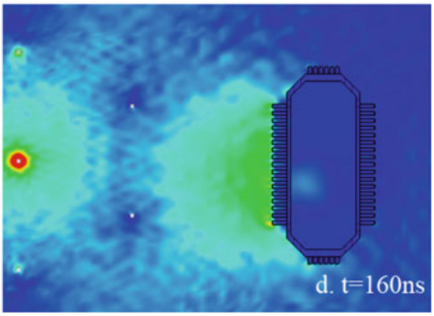
(a) t=70ns.



(b) t=140ns.

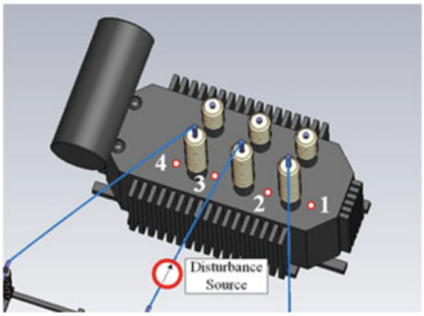


(c) t=150ns.

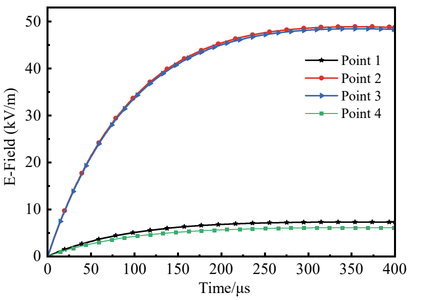


(d) t=160ns.

Fig. 6 Reflection and diffraction of electromagnetic disturbance by transformer shell

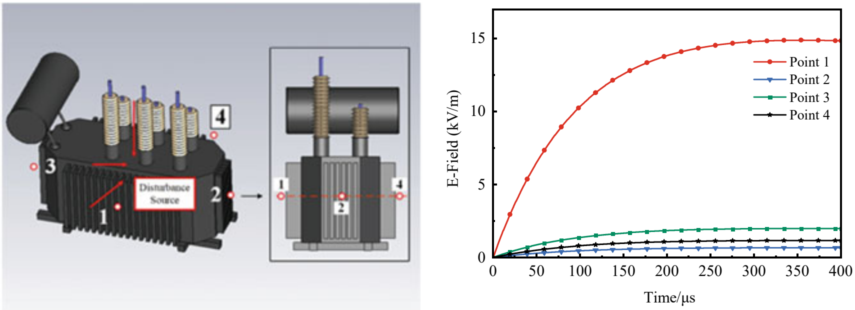


(a) Distribution of measurement points.



(b) Distribution of Electric Field Intensity.

Fig. 7 Electromagnetic disturbance intensity at transformer bushing



(a) Distribution of measurement points. (b) Distribution of Electric Field Intensity.

Fig. 8 Electromagnetic disturbance intensity around transformer

4 Conclusion

This article explains the propagation mode of transient electromagnetic disturbance sources in substations based on the theory of traveling wave antennas. The shielding effect of the metal shell of electrical equipment on electromagnetic radiation was explained through the reflection theory and diffraction theory of electromagnetic waves. Finally, a typical 110kV substation was established through electromagnetic simulation software. The propagation of transient disturbance source in substation under the action of disconnector operation wave and lightning wave is simulated, and the intensity distribution of electromagnetic disturbance in substation is given on this basis. This article provides a basis for subsequent research on electromagnetic interference protection of sensors in substations and the development of more practical electromagnetic compatibility reliability test parameters for sensors.

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