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Analysis of Surge Propagation with Lightning Arrester using FDTD for 25 kV-AC Transmission Line

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Abstract— **This paper analyzes lightning surge propagation and reflection as the surge arrives at a lightning arrester. Telegraphist equations have been used to characterize the voltage and current of a travelling wave in a lossless power transmission line and finite difference time domain (FDTD) method has been used to analyze lightning surge propagation. The characteristics of the reflected wave and transmitted wave have been compared in two cases: (i)using silicon carbide (SiC) arrester, and (ii)using metal oxide varistor (MOV) arrester. The results have shown that, reflected and transmitted waves from the MOV arrester are almost equal in magnitude to those from the SiC arrester, however, the former is more preferable because it has a smoother waveform.**

Index Terms—**Finite Difference Time Domain, Surge Propagation, Lightning Arrester.**

I. Introduction

Overvoltage in an electrical power system results from switching surge and lightning surge caused by the lightning striking on the overhead shield wire with a subsequent flashover to the phase conductor or the lightning directly striking the phase conductor [1]-[4],[16]. The travelling wave or surge propagates and arrives at an electric power component giving rise to shielding failures and faults in the systems [4], [5]. The lightning surge voltage magnitude and waveform dictates the design of the protection system and insulation of the component. A surge arrester protects a power system from the surge propagation by diverting the charge and energy to ground [10]-[12], [18]. A surge arrester model has a non – linear resistive characteristic [10]-[12], Due to impedance change at a transition point, part of the surge is reflected back and the rest passes through. The pass- through surge can cause significant damages to electric power components. Normally, a transmission line is a distributed parameter network composed of inductance and resistance in series and a branch of shunt capacitance and resistance [6], [17]. The telegraphist equation mathematically describes the propagation of the surge voltage and current in transmission lines [7], [8], [15]. These equations are partial differential equations (PDEs). The finite difference time domain (FDTD) method basically approximates PDEs [14], [15].

This paper analyzes characteristics of surge propagation and reflection in a transmission line which uses either SiC arrester or MOV arrester. The FDTD method is used to estimate the reflected wave and the transmitted wave.

The paper consists of seven sections. Section two describes surge propagation. Section three reviews mathematical model of a power transmission line. Surge arrester in power systems is described in section four. Section five presents the FDTD method. Simulation and results are presented in section six. Lastly, conclusion is in section seven.

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II. Surge Propagation

Voltage surges maybe caused by a lightning strike at a conductor, flashover from an air terminal, or switching operation such as opening and closing of a circuit breaker. The surge propagates from the point of disturbance and travels along a transmission line. As the surge propagates past a junction between two components such as transmission lines with different impedances, some part of the surge will refract or pass through the junction called the transmitted wave and the rest will reflect as shown in Figure 1.

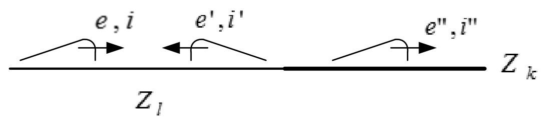

Figure 1: The reflection and refraction of the surge propagation at the junction between two different transmission lines.

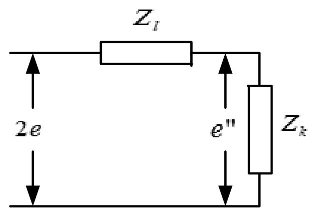

Figure 2: Thevenin equivalent circuit of two different transmission lines.

Where e, i is the voltage and current of the surge propagation.

e', i' is the voltage and current of the reflected wave.

e'', i'' is the voltage and current of the transmitted wave.

Z_l is the impedance of the transmission line 1.

Z_k is the impedance of the transmission line 2.

From the Thevenin equivalent circuit in Figure 2, the surge voltage e" travelling past the junction, and the reflected voltage e' can be obtained in (1) and (2) respectively.

$$e'' = \frac{2Z_k}{Z_1 + Z_k} e \tag{1}$$

$$e' = e'' - e \tag{2}$$

If a junction comprises several different transmission lines as shown in Figure 3, the refracted voltage surge e" is given by (3).

$$e'' = \frac{2Z_t}{Z_1 + Z_t} e \tag{3}$$

where $Z_t = \dfrac{Z_2 Z_3 Z_4}{Z_2 Z_3 + Z_2 Z_4 + Z_3 Z_4}$

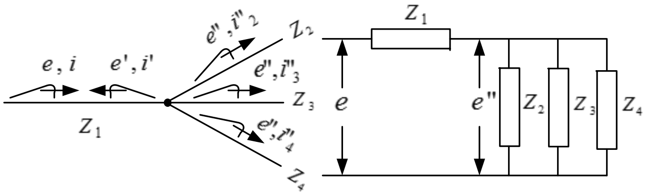

Figure 3: Thevenin equivalent circuit for several transmission lines connected at the junction.

Analysis of a surge propagation moving past a surge arrester installation point uses the same principle as the case of several different conductors connected to the junction. When no surge is presented, the impedance of an arrester is ideally infinite as shown in Figure 4 (b). The voltage across the surge arrester is surge voltage ($e'' = e$) and the reflected voltage is zero ($e' = 0$). When a surge arrives at the arrester, and the arrester starts conducting, its impedance is ideally zero as shown in Figure 4 (c). The voltage across the surge arrester is zero ($e'' = 0$) and the reflected voltage is the opposite of the of surge voltage ($e' = -e$).

In practice however, there exist some voltage across the surge arrester during its operation because the resistance of the surge arrester is non-linear. Accordingly, the voltage across the surge arrester will be tested and provided by the manufacturer.

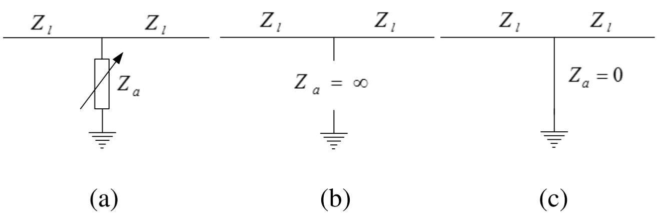

Figure 4: Impedance of the surge arrester in the ideal condition (b) no surge is presented (c) diverting the current to ground.

III. Mathematical Model of a Power Transmission Line

The equivalent circuit of a single-phase transmission line showed in Figure 5 consists of a resistor and inductor in series connected with a branch of resistor and capacitor in parallel in each section. The time-domain characteristics in form of partial differential equations of the single-phase transmission line can be expressed as in (4) and (5).

$$\frac{\partial}{\partial x} v(x,t) = -Ri(x,t) - L\frac{\partial}{\partial t} v(x,t) \tag{4}$$

$$\frac{\partial}{\partial x} i(x,t) = -Gv(x,t) - C\frac{\partial}{\partial t} i(x,t) \tag{5}$$

where

R, L, G and *C* are the line parameters in per unit length.

v(x,t) and *i(x,t)* are the voltage and current.

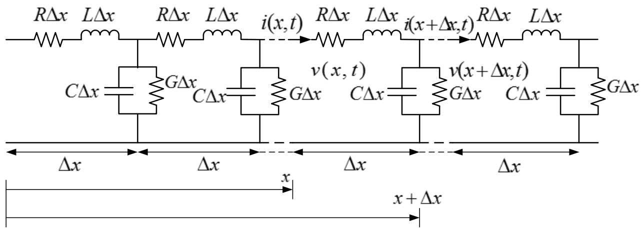

Figure 5: Distributed line model for a power transmission line.

If a transmission line is assumed to be lossless, the R and G in Figure 5 are eliminated (they will be equal to zero). The resulting transmission line model is shown in Figure 6. The partial differential equations of the single-phase transmission line can be expressed as in (6) and (7) which are also known as wave equations.

$$\frac{\partial}{\partial x} v(x,t) = -L\frac{\partial}{\partial t} v(x,t) \tag{6}$$

$$\frac{\partial}{\partial x} i(x,t) = -C\frac{\partial}{\partial t} i(x,t) \tag{7}$$

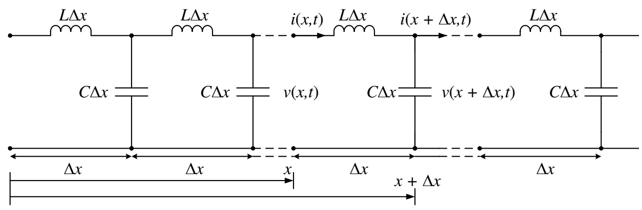

Figure 6: Lossless line model for a power transmission line.

Considering from both (6) and (7), this will produce a linear second-order partial differential equation in form of hyperbolic PDEs as shown in (8) for the voltage wave equation.

$$\frac{1}{LC}\frac{\partial^2}{\partial x^2} v(x,t) = \frac{\partial^2}{\partial t^2} v(x,t) \tag{8}$$

From the voltage wave equation, the finite-difference time-domain (FDTD) method can be used to analyze lightning surge propagation in electric power transmission lines [7]-[9].

IV. Lightning Arrester in a Power System

Lightning arresters protect power systems from lightning surges, by diverting the charge and energy to ground. There are two types of lightning arresters used in medium voltage lines, namely, silicon carbide arresters (SiC) and metal oxide varistor arresters (MOV). This section highlights the characteristics of the two arresters, and describes the algorithm to analyze voltage across an arrester when voltage surge passes through it.

A. Characteristics of a Lightning arrester

The SiC arrester uses a silicon-carbide material (which has a nonlinear resistive characteristic) connected in series with a spark gap. The spark gap provides high impedance preventing the flow of current during normal conditions. When the surge arrives at the arrester, current is allowed to pass through the arrester after the sparkover. The V-I characteristic of the SiC type surge arrester is a combination of both the SiC material and the spark gap [10]. The MOV arrester on the other hand, does not have a spark gap, its V-I characteristic is extremely non-linear such that spark gap is unnecessary [11], [12]. The V-I characteristics of the SiC and MOV arresters are shown in Figure 7.

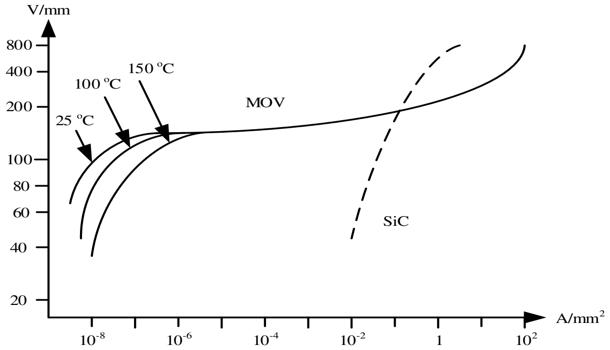

Figure 7: V-I characteristics of the MOV and SiC arresters [1].

Lightning surge test of an arrester in 25-kV system uses 230 kV peak, 10 kA peak discharge current and 8/20 µs waveform. [10], [11]. The sparkover of the SiC arrester from the test occurs at the surge voltage of about 90 kV and the peak voltage across the arrester is 66 kV at 8 µs as shown in Figure 8.

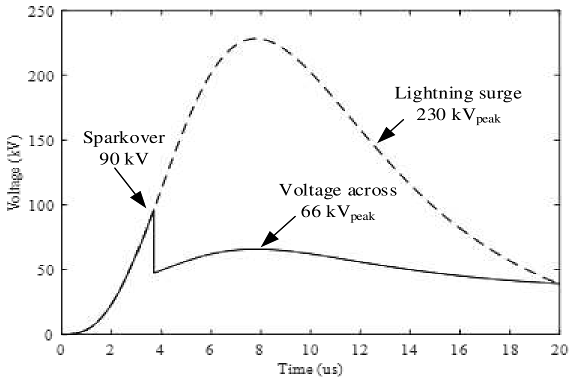

Figure 8: Curves of the surge voltage and the voltage across the SiC arrester.

For the MOV arrester, the peak voltage across the arrester is 70.2 kV at 8 µs as shown in Figure 9.

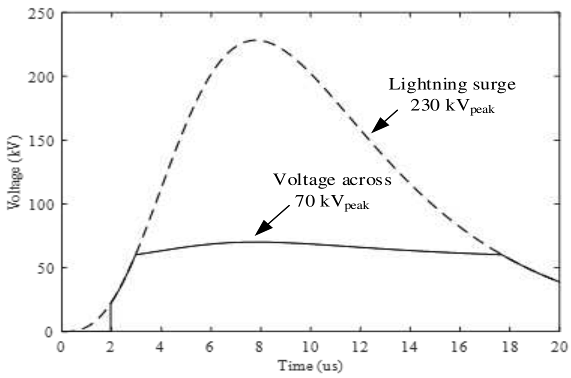

Figure 9: Curves of the surge voltage and the voltage drops across the MOV arrester.

B. Final Stage Algorithm of Lightning Arrester Analysis

The flowchart of the algorithm used to calculate the voltage across the lightning arrester is shown in Figure10.

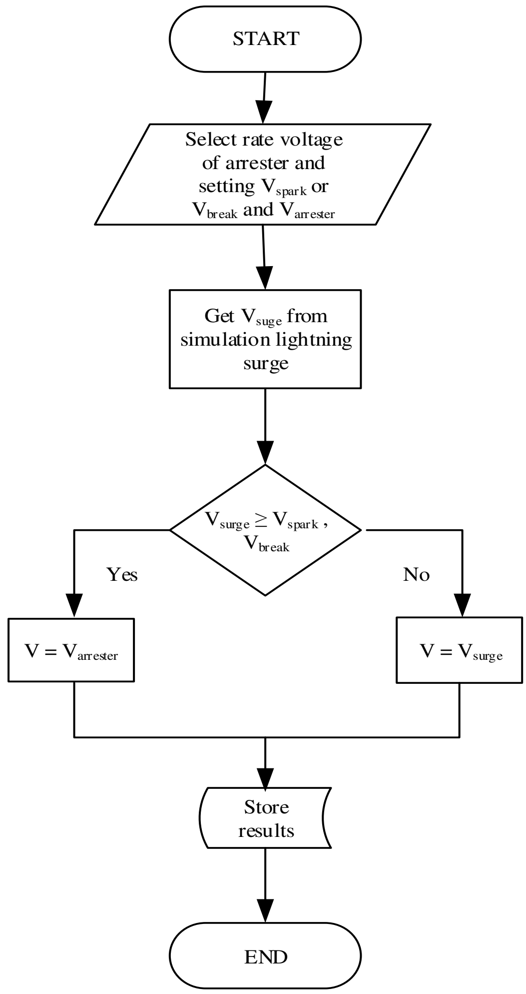

Figure 10: Flow chart to determine the voltage across the arrester.

The first step is to select the rating voltage of the arrester and preset the sparkover voltage (V_{spark}: the voltage level that causes the sparkover at the spark gap) for the SiC arrester and the breakover voltage (V_{break}: the voltage level at which the arrester begins conduction) for the MOV arrester. The values of the peak voltage across the lightning arrester ($V_{arrester}$) are derived from standard tests. Then, obtain a surge voltage from the lightning surge simulation and compare with the sparkover voltage (for the SiC arrester) or the breakover voltage (for the MOV arrester). If the surge voltage is less than the sparkover or breakover voltage, the voltage across the lightning arrester is equal to the surge voltage else the voltage across the lightning arrester is equal to $V_{arrester}$.

V. Finite Difference Time Domain (FDTD) Method

The voltage wave equation in (8) is a hyperbolic PDE. The standard of a hyperbolic PDEs is given in (9).

$$c^2 \frac{\partial^2}{\partial x^2} v(x,t) = \frac{\partial^2}{\partial t^2} v(x,t) \qquad (9)$$

The explicit method of solving the wave equation, replacing the space derivative in the wave equation by the finite difference formula at the λ^{th} time step, (10) is obtained. In the same manner, replacing the time derivative by the finite difference formula at the τ^{th} space step, (11) is formed. By substituting (10) and (11) into (8), it gives the updated voltage wave solution as summarized in (12).

$$\frac{\partial^2}{\partial x^2}v(x,t)=\frac{v(\lambda+1,\tau)-2v(\lambda,\tau)+v(\lambda-1,\tau)}{\Delta x} \quad (10)$$

$$\frac{\partial^2}{\partial t^2}v(x,t)=\frac{v(\lambda,\tau+1)-2v(\lambda,\tau)+v(\lambda,\tau-1)}{\Delta t} \quad (11)$$

$$v(\lambda,\tau+1)=\phi^2 v(\lambda-1,\tau)+2(1-\phi^2)v(\lambda,\tau)+\phi^2 v(\lambda,\tau) - v(\lambda,\tau-1) \quad (12)$$

Where $\phi = c\frac{\Delta t}{\Delta x}=\frac{\Delta t}{\Delta x\sqrt{LC}}$ is the aspect ratio.

VI. Simulation and Results

The simulation program is created by using MATLAB. It takes into account the characteristics of the lightning surge propagation to a lightning arrester. The lightning surge voltage for a simulation has 230 kVpeak and 8/20 µs waveform. The line length of transmission line systems to the lightning arrester is 400 m as show in Figure 11, the inductance and capacitance of transmission lines are 143 µH and 7.5 pF, respectively. The specifications of both types of arresters are given in Table 1.

Table 1. The specifications of SiC and MOV arresters [10], [13].

Voltage ratings = 25 kV, Current Discharge = 10 kA (8/20µs)			
SiC arrester	Sparkover voltage (V_{spark})	90	kV
	Voltage across ($V_{arrester}$)	66	kV
MOV arrester	Brakeover voltage (V_{break})	65	kV
	Voltage across ($V_{arrester}$)	70	kV

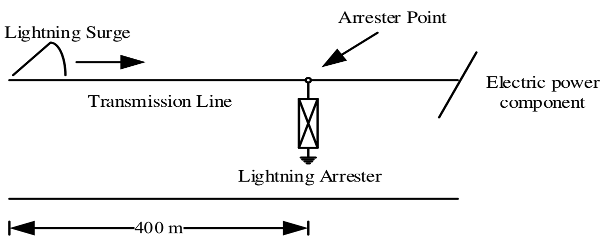

Figure 11: The transmission line system used in the simulation.

The incident wave travelling along the line before hitting the lightning arrester point has 230-kV peak in lossless transmission line systems as shown in Figure 12.

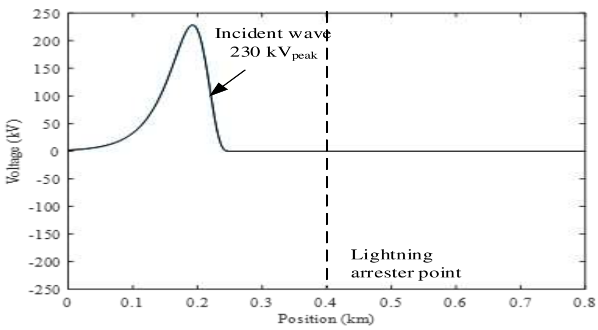

Figure 12: Incident wave before hitting the lightning arrester point.

After hitting the lightning arrester point, the incident wave was separated into the reflected wave and the transmitted wave. The transmitted wave is the voltage across the lightning arrester. These two wave components are shown in Figure 13 and Figure 14.

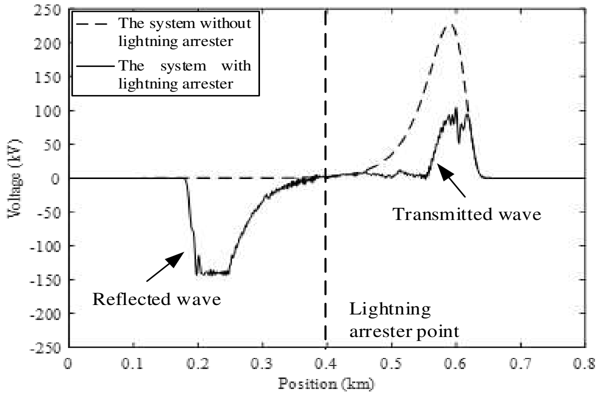

Figure 13: Reflected wave and voltage across the SiC arrester.

The peak voltage across the SiC arrester, as shown in Figure 13, is about 90 kV from the sparkover voltage and the negative peak voltage of the reflected wave is about -164 kV.

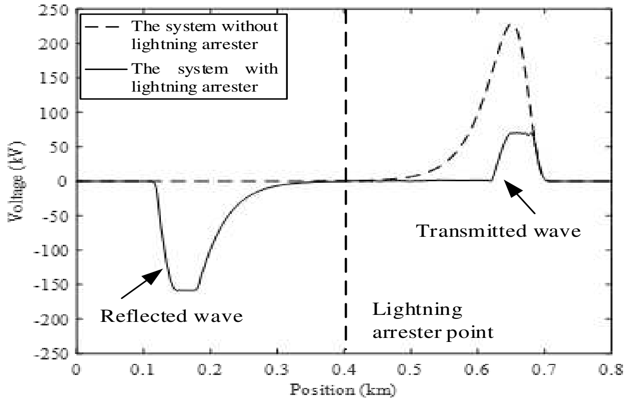

Figure 14: Reflected wave and voltage across the MOV arrester.

For the MOV arrester shown in Figure 14, the peak voltage across the arrester is about 70 kV and the negative peak voltage of the reflected wave is about -160 kV. It can be seen that the reflected and transmitted wave from the MOV arrester are almost equal in magnitude to those from the SiC arrester, however, the former has smoother waveform.

In addition, the full simulation of the whole system having a total of 0.8-km line length, is plotted in Figure 15 and Figure 16 for SiC and MOV arresters respectively.

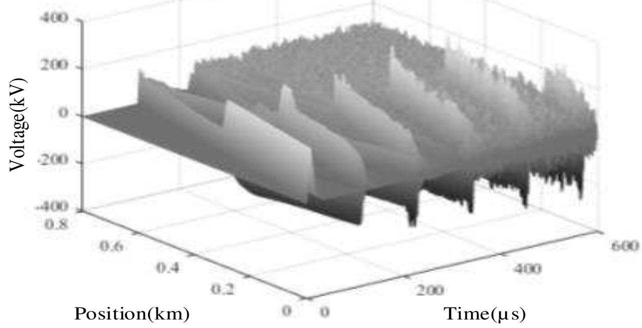

Figure 15: Lightning surge propagation along the transmission lines of the SiC arrester at short circuit line terminal after 600 µs.

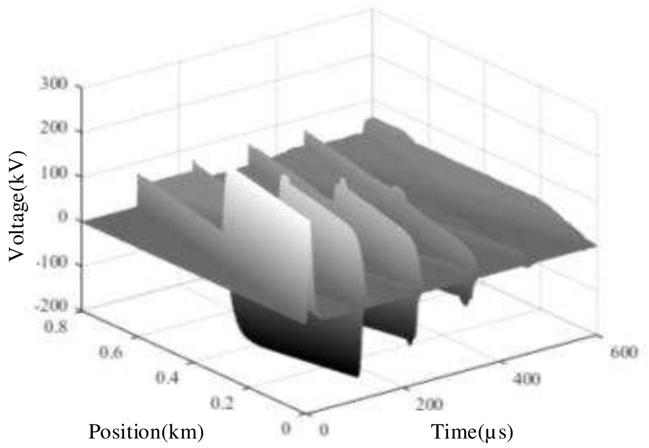

Figure 16: Lightning surge propagation along the transmission lines of the MOV arrester at short circuit line terminal after 600 μs.

VII. Conclusion

This paper analyzes characteristics of surge propagation and reflection in a transmission line that uses either silicon carbide (SiC) arrester or metal oxide varistor (MOV) arrester. The finite difference time domain (FDTD) method is used to estimate the reflected wave and the transmitted wave. The simulation done in MATLAB includes a case where no arrester is used. From the simulation results, it was shown that the incident surge travels along a transmission line to a power equipment without being reflected, if no arrester is used and, the use of the MOV arrester has a slight advantage over the use of the SiC arrester due to the smoother reflected and transmitted wave.

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