https://doi.org/10.1016/j.epsr.2015.11.034

Surges Induced in Building Electrical Systems during a Lightning Strike

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Abstract—**This paper presents an investigation into lightning surges induced in buildings with the FDTD method. When down conductors (DCs) in a building discharge a lightning current, induced surges are observed in adjacent distribution circuits due to electric and magnetic coupling. The induced voltage in an open circuit and the induced current in a close circuit are respectively determined by the current surge and voltage surge on the DC. It is found that connected capacitors can reduce the induced surge voltages, but may not be effective. SPDs are then recommended installing at two far ends of a distribution circuit. They are not required to dissipate substantial lightning surge energy observed in the down conductors. The surge currents in SPDs can be estimated using the closed-form formula.**

Keywords- lightning current, induced surge, LV distribution circuit, FDTD

1. INTRODUCTION

Electronic equipment has proliferated in buildings to meet the ever-increasing demand of businesses. Such equipment is susceptible to electrical disturbances generated by lightning. In the past few years the surge environment in buildings has become worse, particularly when insulated down conductors were adopted in lightning protection systems. To protect sensitive equipment against lightning it is necessary to evaluate and characterize the surge environment in buildings.

Lightning surges in buildings can be generated via (a) inductive/capacitive coupling and (b) resistive coupling. The mechanism of resistive coupling has been discussed widely in past decades [1-2]. The surge currents/voltages dispersed on low voltage systems have been analyzed under different scenarios, and were well documented [3-5]. Location categories have been introduced in IEEE standards [7-9]. The lightning surges experienced in buildings have been characterized, and the waveform and amplitude of the surges in different locations have been specified. These surges generally impinge at the service entrance from the circuits outside the buildings. However, little work has been done on the surges arising from inductive/capacitive coupling in buildings during a direct lightning strike.

This paper presents an analysis of induced surge voltages and currents in a building distribution system during a direct lightning. The building is protected by a lightning protection system with insulated down conductors placed in the vicinity of building distribution circuits. In this paper both the lightning protection system and distribution circuits are modeled using the Finite-Difference Time-Domain (FDTD) method. Simulations are then performed to study the induced surges in the distribution circuits. Different circuit parameters, such as spacing and distance, are considered in the study, and their impact on the induced surges is revealed. The impact of loads connected to the circuits is investigated as well. A protective measure for suppressing induced surges in a distribution system is presented finally. This is an extended version of the paper submitted to ICLP2014 [12].

2. SIMULATION MODELS

Insulated down conductors (IDCs) are adopted in modern buildings. They are installed in electrical duct, and run in parallel with power distribution circuits. When a building is struck by lightning, the lightning current in the down conductors emits electromagnetic fields and propagates downwards to the ground. The lightning electromagnetic pulses will induce surge voltages and currents in the adjacent conductors, such as distribution power cables. These conductors are finite in length, and run vertically above the ground. The traditional transmission line theory is not applicable for surge analysis in such cases. The FDTD method is then applied to study the induced surge voltages and currents in these conductors.

The power distribution circuits in the buildings are made with single-core cables. These cables run vertically from distribution transformers to users' equipment on different floors. Note that a transformer is normally modeled as an entrance capacitance in fast transient analysis. For simplicity of discussion, the entrance capacitance is removed in the reference configuration, as shown in Fig. 1.

Fig. 1 shows the configuration of a simplified system under investigation. It consists of a single down conductor and two single-core cables situated over the ground. For worst-case analysis the contribution from the currents in other DCs is not taken into account. The down conductor is represented by a 90m-tall cylinder with the radius of 5mm. It is connected to a perfect ground via a 100ohm lumped resistance, and to a current source at other end. An upward conductor is placed at the upper end to mimic a lightning channel. Two distribution cables are modeled by cylinders as well with the height (l_0) of 30m and the radius (r_0) of 5mm. The distances of the down conductor to two conductors are r_1 and r_2, respectively. In the reference case, both r_1 and r_2 are equal to 0.5m and 0.7m, respectively. The bottom end of the distribution circuit is 60m away above the ground. A lightning return stroke current is injected at the top end of the down conductor.

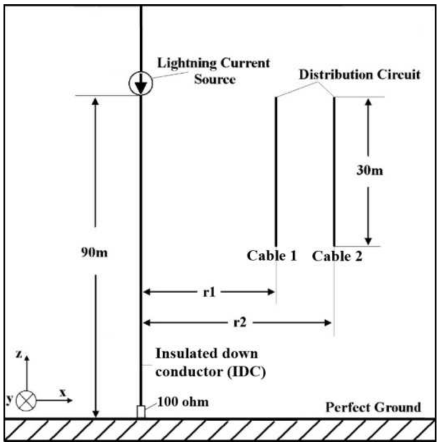


Fig.1. Configuration of the down conductor and an adjacent distribution circuit

The working volume of the simulation model is 4m×4m×92.1m. It is surrounded by six planes of perfectly-matched layers (PML) with absorbing boundary conditions being enforced. There are seven layers of the absorbing surfaces in the model, so that the reflection wave on the planes can be effectively minimized [10]. It is assumed that the upward conductor runs to infinity, and no reflected surge in the upward channel travels back to the down conductor. PML absorbing boundary conditions are then applied at the height of 92.1m in the simulation model. The working volume is divided into cuboid cells. The side length of cuboid cells in the z-direction is 50mm near the conductors, and is increased to 500mm gradually to the boundary. The side lengths in the x and y directions are 0.5mm near the conductors, and are increased to 500mm gradually. Time step is determined by the Courant condition,

$$\Delta t \le \frac{1}{c\sqrt{\dfrac{1}{(\Delta x)^2}+\dfrac{1}{(\Delta y)^2}+\dfrac{1}{(\Delta z)^2}}} \qquad (1)$$

where c is the speed of light, and $\triangle$x, $\triangle$y, $\triangle$z are the side lengths of the smallest cell in meter.

3. INDUCED SURGES IN OPEN CIRCUITS

A subsequent return stroke current was applied in the simulation to investigate induced surges in the distribution circuit. The current source was a fast-front pulse with the rise time of 0.3μs and the amplitude of 10kA. Fig. 2 shows waveforms of the surge current (I_{IDC}) at different positions of the down conductor. Because of the surge reflection on the ground the surge current at a lower position of the down conductor is generally higher. The oscillation frequency is determined by the travel time of two round trips on the IDC. As the induced surge is greatly affected by the wave front of an injected surge, time-domain results of the surges for the time period of 2μs are given in the figures.

The induced voltages in a distribution circuit without any connected load were simulated as well. For comparison, the 10kA source current with the rise time of 0.2μs, 0.3μs and 1.0μs was respectively applied in the simulations. The results are presented in Fig. 3. It is observed that the induced voltage increases when the surge propagates downwards. When a reflected surge travels back, the induced voltage tends to decline and continues to oscillate with the surge voltage on IDC. It is also found that the induced surge voltage does not vary significantly when the rise time of I_{IDC} is changed from 0.2μs to 0.3μs. However, the induced surge voltage is reduced significantly in the case of 1.0μs rise time. This is because the reflected surge travels back to the observation point before the surge current reaches its peak value, as seen in Fig. 3.

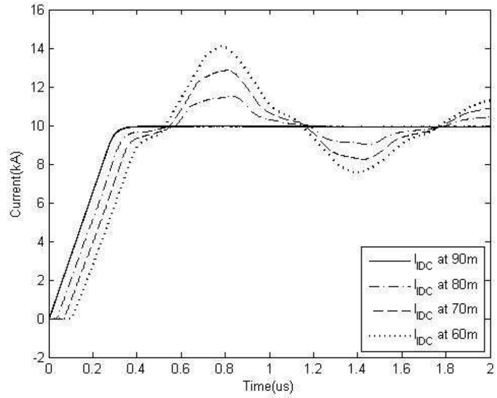


Fig. 2 Surge currents (I_{IDC}) along the down conductor at different heights

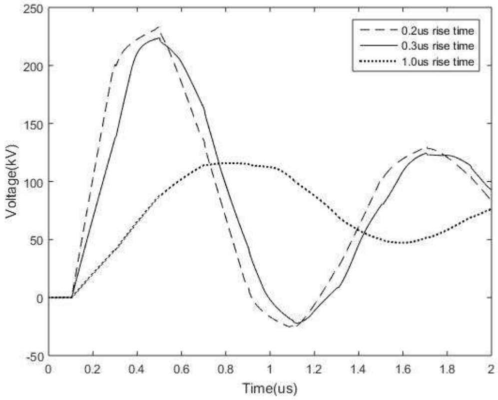


Fig. 3 Induced voltage at the bottom end of the distribution circuit

Computer simulation was also performed to investigate the effect of the distance to the distribution circuit. As the surge voltage was induced between two phase conductors of the circuit, distances of two phase conductors r_1 and r_2 to the IDC were of concern. The peak voltage in the distribution circuit was then evaluated by varying distances r_1 and r_2.

The induced voltage at the bottom end of the distribution circuit was computed with different values of distances r_1 and r_2. Tables 1 and 2 show respectively the peak values of the voltage when the spacing d (d=r_1-r_2) is fixed to be 200mm, and the distance r_1 is fixed to be 0.5m. It is noted that the peak value of the voltage decreases with increasing distance to the phase conductor, but increases with increasing conductor spacing. Further investigation reveals that the surge amplitude is linearly proportional to a logarithmic function of r_2/r_1. Tables 1 and 2 also present the verification results in two cases, that is, (1) with variable r_1, and (2) with variable d.

Table 1 Ratio K of peak voltage to $\mathbf{ln}\ (\boldsymbol{r_2/r_1})$ with variable $\boldsymbol{r_1}$ (d is fixed)

r_1	Peak Voltage (kV)	r_2/r_1	$\ln(r_2/r_1)$	K (kV)
0.5m	224.0	0.7/0.5	0.336	666.6
1.5m	82.06	1.7/1.5	0.125	656.5
2.5m	49.62	2.7/2.5	0.077	644.4

Table 2 Ratio K of peak voltage to $\mathbf{ln}\ (\boldsymbol{r_2/r_1})$ with variable d ($\boldsymbol{r_1}$ is fixed)

d	Peak Voltage (kV)	r_2/r_1	$\ln(r_2/r_1)$	K (kV)
0.2m	224.0	0.7/0.5	0.336	666.6
0.5m	462.3	1/0.5	0.693	667.2
1.0m	728.8	1.5/0.5	1.098	663.7

4. INDUCED SURGES IN SHORT CIRCUITS

4.1 Induced surges in a circuti with two close ends

In this case, the distribution circuit is shorted at both two ends, which mimic a short circuit at two ends or connection of SPDs to the circuit. There are apparently zero surge voltages at two far ends because of the short circuit. Induced currents are however observed along the distribution circuit between two ends.

Fig. 4 shows the waveforms of induced currents at two ends of the distribution circuit when a lightning current is injected at the top end of the down conductor. It is known from the figure that the induced current at the top end has a waveform similar to that of the source current. It reaches 475A approximately around 0.3μs. However, the surge current at the bottom end has a waveform and a peak value different from those of the current on the top end although they are in the same closed loop. The difference is primarily caused by the surge reflection of the IDC current at the ground.

For comparison, induced current using the low-frequency approximation was evaluated as well. At low frequency only magnetic coupling caused by the current on the down conductor is considered. Assume that the distribution circuit is made of perfect electrical conductors and the source current remains the same along the IDC. According to the Faraday's law, magnetic flux contributed by the source current is balanced by induced currents I_{cab1} and I_{cab2} on two conductors of the close loop, that is,

$$\Phi_{IDC-loop} = \Phi_{cab1-loop} + \Phi_{cab2-loop} \tag{2}$$

where Φ_{X-loop} represents the magnetic flux of the close loop associated with the current in conductor X. The flux per unit length in the z direction is expressed by

$$\begin{aligned} \Phi_{IDC\cdot loop} &= \int_{r_1}^{r_2} \frac{\mu_0 I_{IDC}}{2\pi x} \cdot dx \\ \Phi_{cab1\cdot loop} &= -\int_{r_0}^{r_2-r_1} \frac{\mu_0 I_{cab1}}{2\pi x} \cdot dx \\ \Phi_{cab2\cdot loop} &= \int_{r_0}^{r_2-r_1} \frac{\mu_0 I_{cab2}}{2\pi x} \cdot dx \end{aligned} \tag{3}$$

Substituting (3) into (2) yields an equation for both the induced currents and IDC current. Note that the IDC current varies with position on the IDC. The average induced current I_{avr} at position z on the distribution circuit is determined approximately by

$$\begin{aligned} I_{avr}(z) &= \frac{-I_{cab1}(z) + I_{cab2}(z)}{2} \\ &= \frac{\ln(r_2/r_1)}{2\ln\left[(r_2-r_1)/r_0\right]} \cdot I_{IDC}(z) \end{aligned} \tag{4}$$

Both induced currents I_{cab1} and I_{cab2} in (4) are generally different. However, they tend to be the same at two far ends.

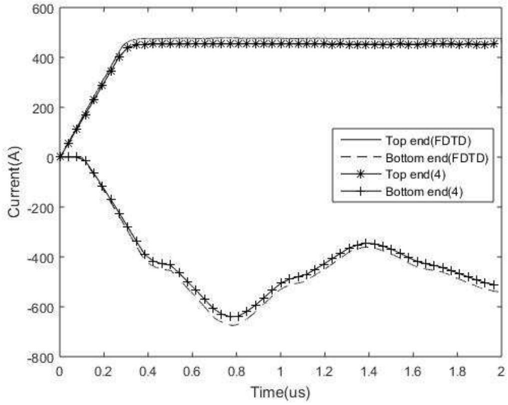


Fig.4 Induced currents at two far ends of a shorted distribution circuit

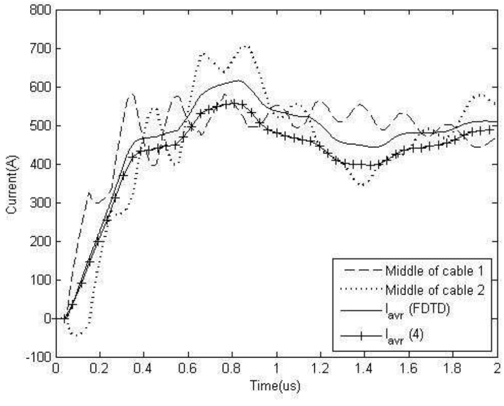


Fig.5 Induced currents at the middle of a shorted distribution circuit

The results made with the FDTD method and the low-frequency approximate formula are presented in both Fig. 4 and 5. Fig. 4 shows the surge currents at the two far ends of the distribution circuit. It is seen that the current waveforms match very well, and the difference of surge currents is generally less than 5%. Fig. 5 shows the surge currents at the middle of the distribution circuit (75m above the ground). It is found that both I_{cab1} and I_{cab2} calculated with the FDTD methods are significantly different, and are different from the estimated result with (4). However, the waveform of the average current matches well with the low-frequency approximate result, as shown in Fig. 5. The difference in magnitude between the FDTD and estimated results of the average current at the middle point is less than 9%.

4.2 Induced surges in a circuti with one open end and one close end

Fig. 6 shows the induced voltage along the distribution circuit when the top end is close and the bottom end is open. It is found that the induced voltage is not equal to zero although a short circuit is made at the top end. The amplitude of oscillation voltage increases gradually towards the open end, and reaches the maximum at the open end. The peak value of the induced voltage can reach 170kV.

When a surge propagates downwards on the IDC, induced voltage in the distribution circuit remains zero initially. This is due to the interaction between the IDC current and induced current in the circuit. When the induced surge arrives at the bottom end, a substantial voltage is observed there. This is because the induced surge current in the distribution circuit could not go further at the bottom end, and a full reflection of surge voltage yields at this location. The induced surge current then travels back towards the close end, and generates the surge voltage along the circuit.

The surge current continues to propagate along the circuit, and has subsequent reflections at the top end (short circuit) and at the bottom end (open circuit). This leads to an oscillation waveform for the surge voltage in the circuit. The oscillation frequency is determined by the travel time of two round trips. This is because the surge current in a circuit with one open end and one close end changes its polarity for a time period of a round trip. The induced voltage at other location has the same pattern as that at the open end. The magnitude of the induced voltage at other location is less generally, as seen in Fig. 6.

Similar to the induced current in the closed loop, induced voltage at the open end is estimated using the magnetic coupling formula. Induced voltage V_{ind} due to low-frequency magnetic coupling is expressed by

$$V_{ind}(z) = \frac{\mu_0 l_0}{2\pi}\ln\left(\frac{r_2}{r_1}\right)\cdot\frac{dI_{IDC}(z)}{dt} \tag{5}$$

where l_0 is the length of the distribution circuit. Fig. 7 shows the induced voltage calculated with (5) at the bottom end of the distribution circuit. It is found that induced voltage calculated with (5) is totally different from that obtained with the FDTD method. The low-frequency result is proportional to the derivative of the IDC current, and decays quickly as the current derivative becomes small. The FDTD result is an oscillation surge. The amplitude gradually increases to its peak level, and then decays to zero. This is because electric coupling at the open end is significant, but is not taken into account in the low-frequency approximation.

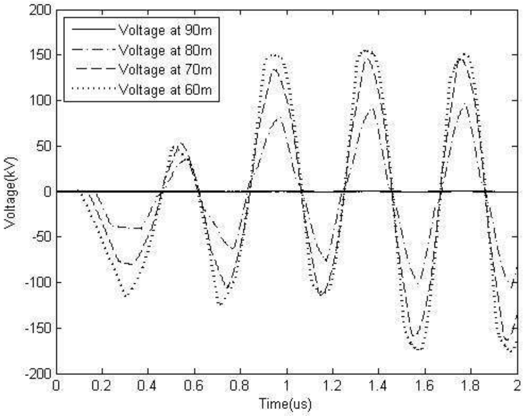


Fig. 6 Induced voltages on the distribution circuit with one open end and one close end

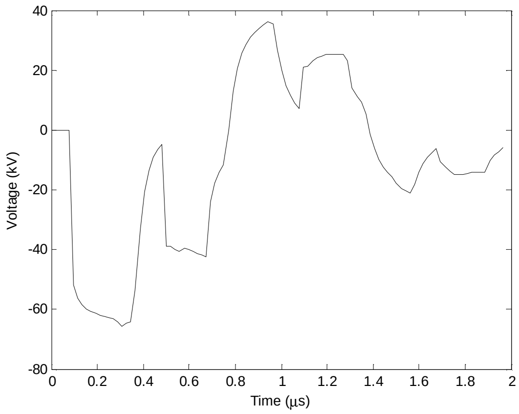


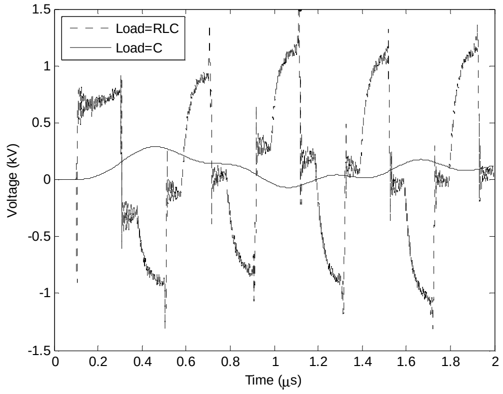
Fig. 7 Induced voltages on the distribution circuit with the open end and the close end with the approximate formula

5. INDUCED SURGES IN LOADED CIRCUITS

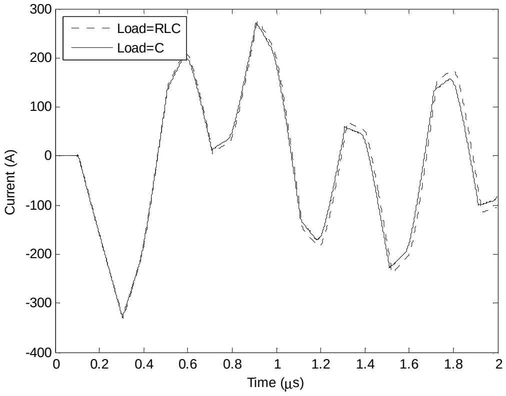
Most of equipment used in buildings has an input circuit (e.g., EMI filter). It is connected to the supply circuit even in standby mode. The input circuit generally has a capacitor, which could suppress the surge induced on the distribution circuit connected. The effect of an input capacitor on induced surges in a distribution circuit is then investigated in this section.

In the simulation the distribution circuit was loaded with a capacitor at the bottom end, and was open or close on the top end. The capacitor placed at the circuit was an "X" capacitor, which is normally used in EMI filters for switching mode power supply. Two different models of the capacitor were considered in the simulation. Model A was a pure capacitance of 0.22uF. Model B was a series RLC circuit with R=0.122ohm, L=0.38uH and C=0.22uF. In the second model the frequency response of the capacitor was taken into account.

Fig. 8(a) shows the waveforms of the surge voltage at the capacitor using these two different models when the top end is open. It is found that the peak voltage across the Model A capacitor reaches 300V. Compared with the results in Fig. 2, the pure capacitance can suppress the induced surge voltage significantly. The induced voltage is highly affected by rise time or change rate of the injected surge current. When the Model B capacitor is connected to the distribution circuit, the induced surge voltage is increased to several kilo-volts. This is caused by stray inductance of the capacitor, which exists physically in a practical component. The oscillation of the induced surge voltage is determined by the multiple reflections of the surge current on the IDC.



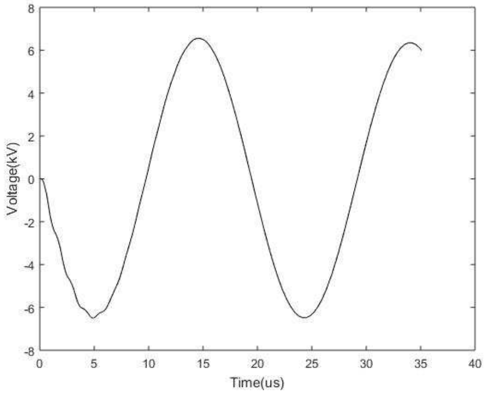
(a) Surge voltages



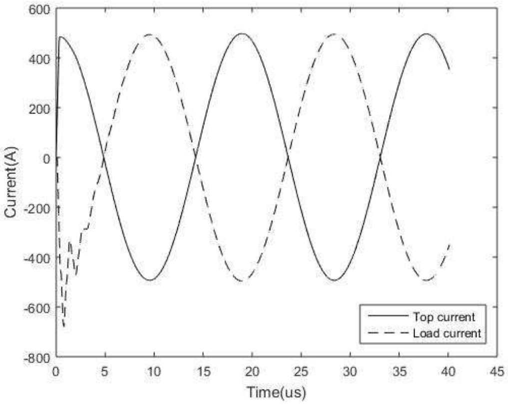
(b) Surge currents

Fig. 8 Surge voltages and currents on the loaded circuit with an open end on the top

Fig. 8(b) shows the waveforms of the surge current on the capacitor. As the circuit eventually behaves like an open circuit, the induced current on the capacitor decays quickly to zero. It is also found that the surge current under two different models matches well. This shows that the surge current does not change significantly, as long as the variation of load impedance is small.



(a) Surge voltage



(b) Surge current

Fig. 9 Surge voltage and currents on the loaded circuit with a close end on the top

Fig. 9 shows the waveform of both surge voltage and surge currents when the distribution circuit is shorted at the top end. In this case the distribution circuit is loaded with a Model A capacitor. It is found that the surge currents are very similar to those in the case of a short circuit in the early period of time, and are primarily determined by the IDC current. This is because the capacitor behaves like a short circuit at high frequency. Both induced voltage and current eventually have slow-oscillation waveforms, as seen in Fig. 9. Actually a resonant circuit is formed by the capacitance at the bottom end and the equivalent inductance of the distribution circuit. It is noted that the capacitor voltage reaches 6.5kV in peak, and is much higher than that when the top end is open. It could cause damage to the capacitor or connected loads. However, this voltage is much lower than the induced voltage when the distribution circuit is open at two ends.

6. PROTECTION OF INDUCED SRUGES WITH SPDS

Surge protective devices (SPDs) are effective in suppressing lightning surges propagating in the distribution circuits. In modern high-rise buildings, lightning surges may impinge at a service entrance, or be induced from the down conductor. In the later case, the surges will propagate downwards from the top end of the distribution circuit. To suppress induced lightning surges, it is necessary to install a SPD at the top end. It is noted from Section IV that the induced surge continues to increase towards the bottom end even if a short circuit is made at the top end. A second SPD then is required at the bottom end to suppress the surge there. This pair of SPDs also serves to suppress any surge impinging at the service entrance from the circuit outside. Fig 10 illustrates the protection scheme adopted for the distribution circuit within a building.

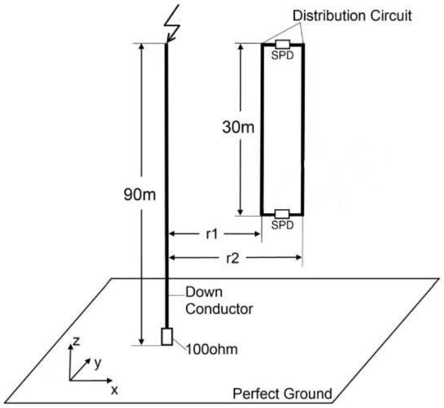


Fig. 10 Protection scheme for a building distribution circuit

Computer simulation of induced surges was performed using the model shown in Fig. 10. Both SPDs in the model have a residual voltage of 1150V, and actually provide a means of a short circuit under the lightning surge environment. The simulation results of SPD voltages and currents are presented in Fig. 11 and 12. It is noted from the figures that surge voltages at both ends are limited to the residual voltage of SPDs. It is also noted that the surge currents in the SPDs are very similar in waveform to those found in the short circuit, and are determined by I_{IDC}. This indicates that induced current in a closed loop can be treated an independent current source, and is not affected by load impedance significantly. It is noted that in Annex E of IEC standard 62305-1 [11] that the induced current has a waveform of 8/20μs in a closed loop, given by a 10/300μs lightning return stroke current to a structure. This is different from what is found in this study. The SPD currents are found to be small generally, and are just a few hundred Amperes in peak, compared with the 10kA in the down conductor. Therefore, SPDs installed in the distribution circuit are only used to limit the surge voltages, and are not required to dissipate substantial lightning surge energy observed on the IDC.

7. CONCLUSIONS

This paper presented a numerical investigation into lightning-induced surges in building distribution circuits. When the lightning current to the building is discharged by an insulated down conductor, substantial induced surges are generated in the adjacent circuits due to both electric coupling and magnetic coupling. The induced surges are different from those obtained using quasi-static models.

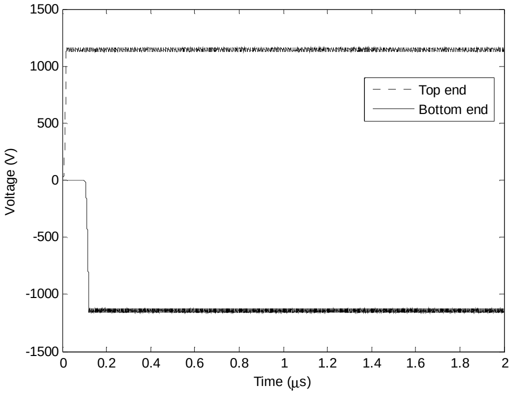


Fig. 11 Surge voltages on the circuit with SPDs installed at two ends

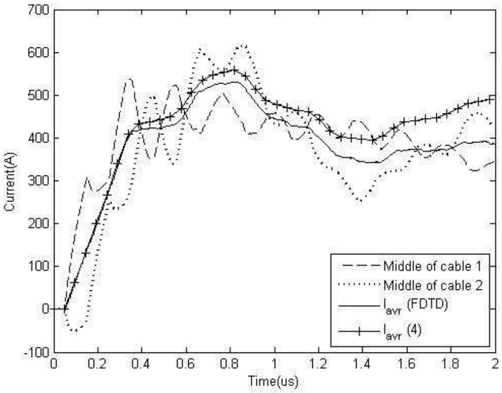


Fig. 12 Surge currents in the circuit with SPDs installed at two ends

It is concluded that the induced voltage in an open circuit is determined by surge voltage on the IDC, and the induced current in a close circuit by surge current on the IDC. Both induced voltage and current are proportional to a logarithmic function of the ratio of distances to two circuit conductors. It is found that capacitors connected to the circuit can reduce the induced surge voltage, but may not be effective in suppressing the voltage down to an acceptable level. It is recommended installing SPDs at two far ends of a distribution circuit. As the surge currents are relatively small, those SPDs are not required to dissipate substantial lightning surge energy observed on the down conductor. It is also found that the surge currents in SPDs are very similar to those in short circuits. The induced current can be treated as an independent source current. It is determined by the current in the down conductor, and has a waveform similar to the down-conductor current. The surge induced current can be estimated using a low-frequency approximate formula.

ACKNOHLEDGMENTS

The work leading to this paper was supported by grants from the Research Committee of the Hong Kong Polytechnic University, and the Research Grants Council of the HKSAR (Project No. 5148/13E and 152044/14E).

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Figure(s)

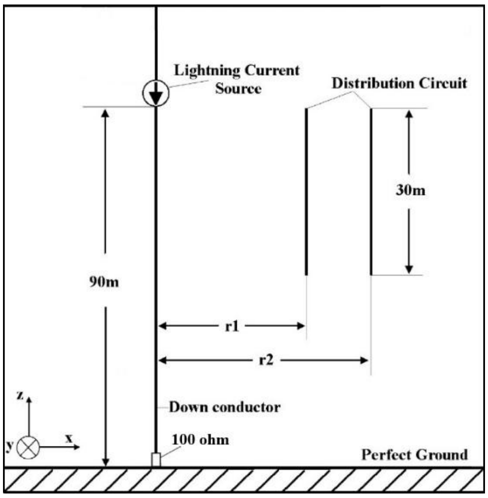


Fig.1. Configuration of the down conductor and an adjacent distribution circuit

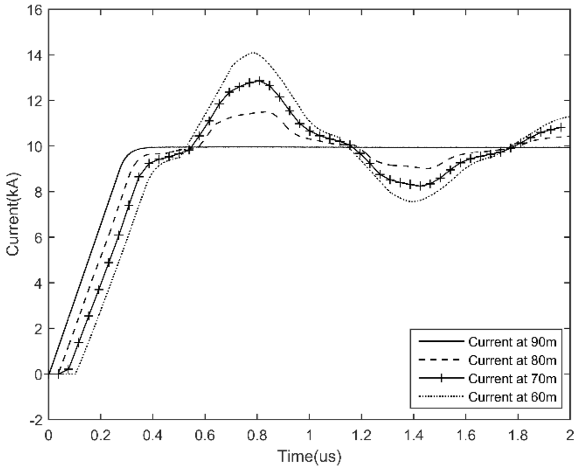


Fig. 2 Surge currents (I_{IDC}) along the down conductor at different heights

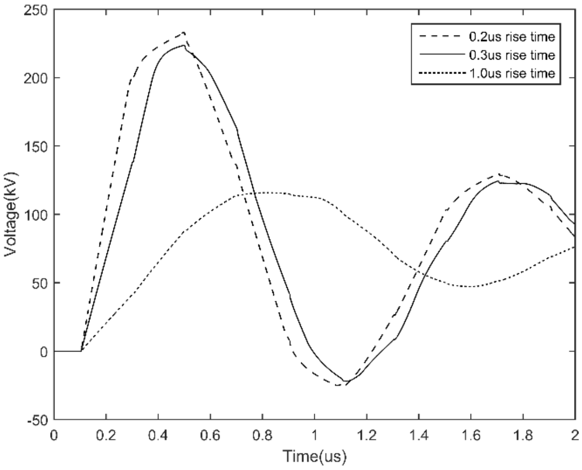


Fig. 3 Induced voltage at the bottom end of the distribution circuit

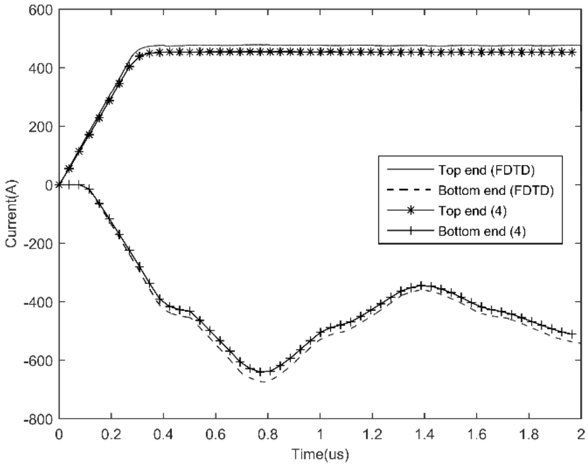


Fig.4 Induced currents at two far ends of a shorted distribution circuit

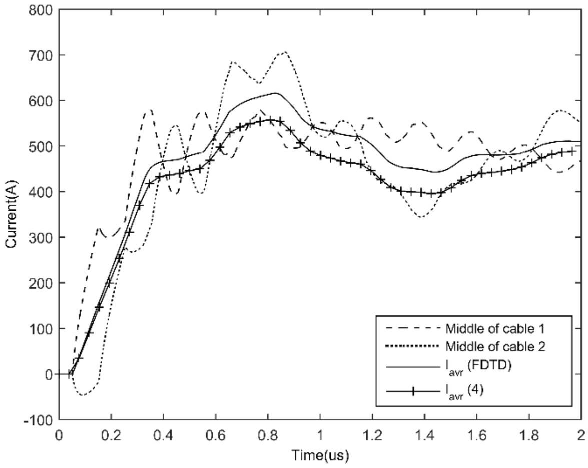


Fig.5 Induced currents at the middle of a shorted distribution circuit

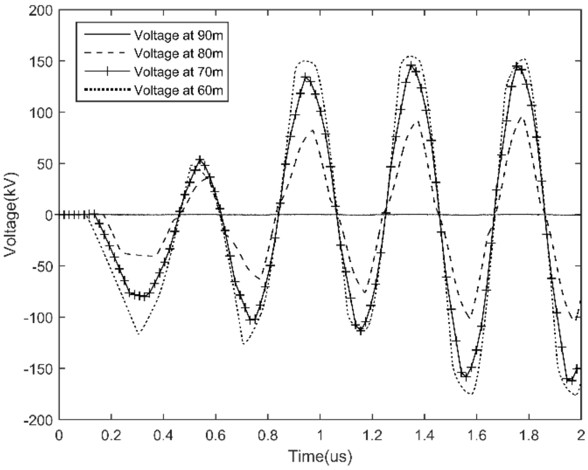


Fig. 6 Induced voltages on the distribution circuit with one open end and one close end

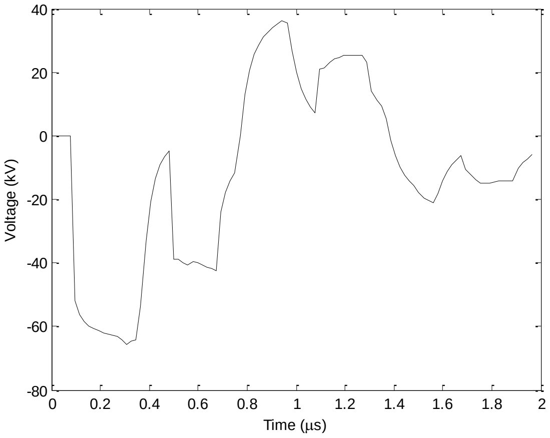
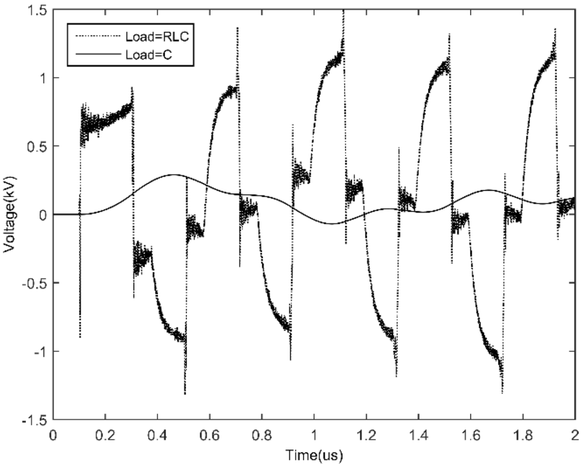
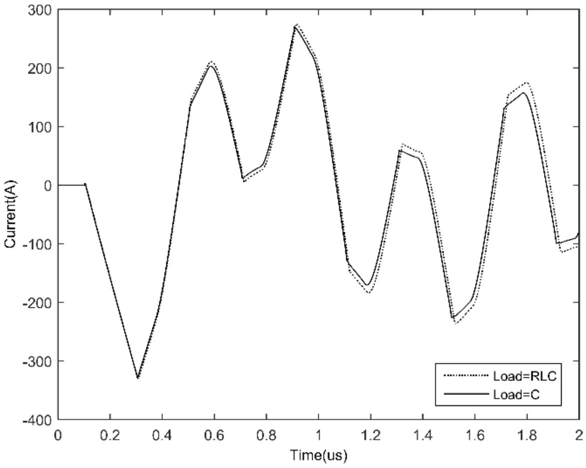


Fig. 7 Induced voltages on the distribution circuit with the open end and the close end with the approximate formula

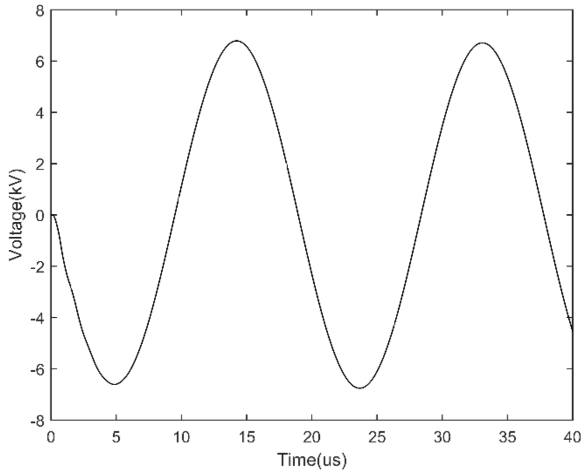


(a) Surge voltages

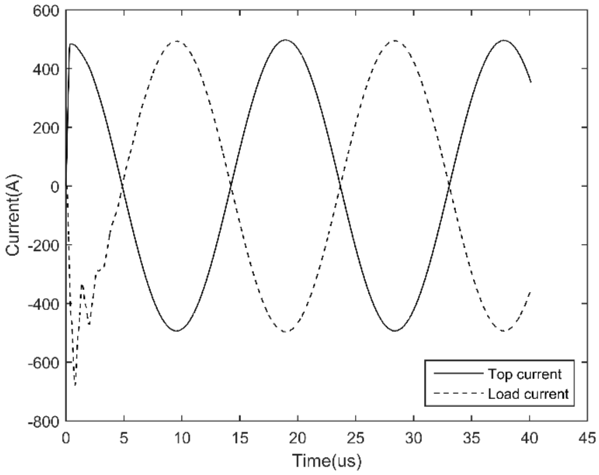


(b) Surge currents

Fig. 8 Surge voltages and currents on the loaded circuit with an open end on the top



(a) Surge voltage



(b) Surge current

Fig. 9 Surge voltage and currents on the loaded circuit with a close end on the top

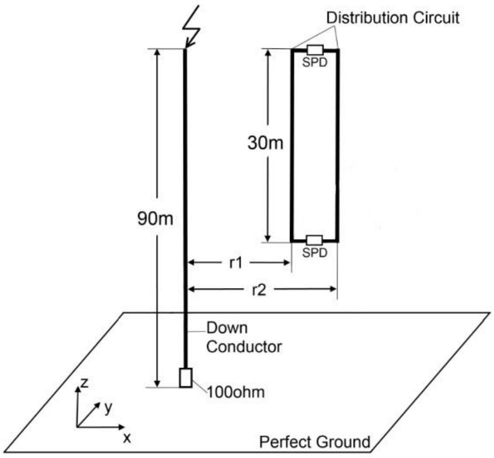


Fig. 10 Protection scheme for a building distribution circuit

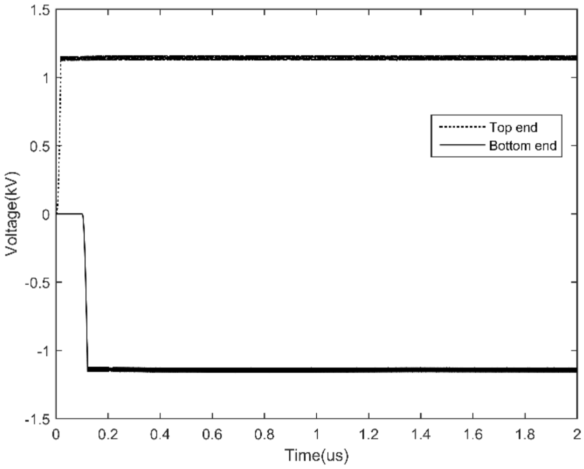


Fig. 11 Surge voltages on the circuit with SPDs installed at two ends

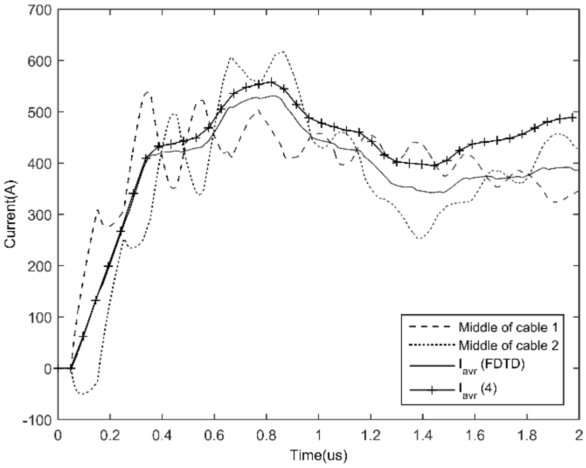


Fig. 12 Surge currents in the circuit with SPDs installed at two ends