Short Papers

Discussion on Worst Distance Between SPD and Protected Device

Shunchao Wang and Jinliang He

***Abstract*—It is commonly known that the longer the distance between a surge protective device (SPD) and a protected device, the worse the protection effectiveness. However, we observed there exists a worst distance between an SPD and a protected device in a low-voltage circuit. If a protected device and an SPD are separated by this worst distance, the protected device will be subject to the most severe surge voltage. The main reason for this phenomenon is that there usually exist two reflection processes, namely, that between the transformer and the SPD and that between the SPD and the protected device. These two refection processes lead to the superposition of voltage wave in a way that is different from that in the high-voltage circuit. This paper presents an analytical formula to estimate this worst distance. It is also shown that the result obtained from the formula has a good agreement with the simulation in PSCAD/EMTDC.**

***Index Terms*—Low-voltage power circuits, pole transformer, protection distance, surge protection device (SPD), surge reflection phenomena, surge voltage, transient propagation.**

I. INTRODUCTION

Lightning is a major electromagnetic interference in the electrical systems. Its interaction with low-voltage circuits has been studied for a long time. One of the issues in this field is about the surge protection devices (SPDs). SPDs are widely used in the low-voltage power circuits to damp the invading voltage surge from the transmission line. The distance between an SPD and a protected device is one of the important factors influencing the protection effectiveness of the SPD [1]–[3]. A commonly known fact of the protection distance of a surge arrester is that the closer the protected device is to the surge arrester, the better the protection is. However, during our study, we found it is not the case for low-voltage circuits. For a typical low-voltage network, as illustrated in Fig. 1, the lightning overvoltage on a 10-kV distribution line caused by direct or indirect lightning strikes will propagate to the 220-V side through the power transformer [4]–[6]. An SPD is usually installed between the transformer and the terminal device. Due to this circuit topology, there exist two reflection processes, namely, that between the transformer and the SPD and that between the SPD and the protected device. This paper shows that the superposition of waves reflected from different terminals leads to the exaggeration of the surge voltage. Due to this phenomenon, there exists a worst distance between the protected device and the SPD (denoted as D_{worst} in this paper), when the electric device is installed D_{worst} away from the SPD, it will be subject to the most severe surge voltage. We give a simple analytical formula to calculate D_{worst}. The formula's accuracy is shown to be at a reasonable level after being compared to the simulations in PSCAD/EMTDC.

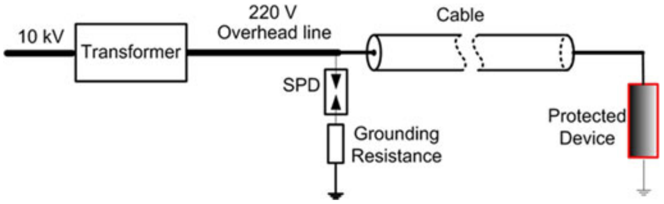

Fig. 1. Configuration of low-voltage network studied in this paper.

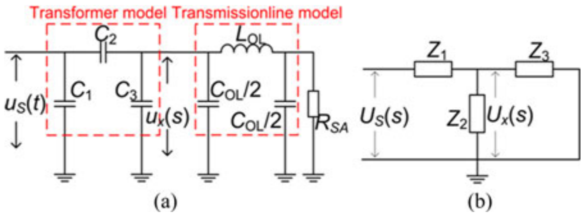

Fig. 2. (a) Equivalent circuit model and (b) simplified circuit model of Fig. 1. C_{OL} and L_{OL} are the total capacitance and inductance of the 220 V overhead line; C_1, C_2, and C_3 constitute the transformer model [4]; $Z_1 = 1/(sC_2)$, $Z_2 = 1/(s(C_3 + C_{\mathrm{OL}}/2))$, and $Z_3 = sL_{\mathrm{OL}}$. $u_S(t)$ and $u_x(t)$ are the surge voltage and the voltage on the left terminal of 220-V overhead line; $U_S(s)$ and $U_x(s)$ are their frequency expression.

II. SIMPLIFIED MODEL TO CALCULATE THE WORST DISTANCE BETWEEN SPD AND PROTECTED DEVICE

In order to simplify the deduction, the following assumptions are adopted.

1) The refraction voltage wave from cable to the 220-V overhead line can be neglected. In other words, the voltage on the 220-V line consists of the voltage transferred from the transformer and the voltage reflected by the SPD. This is mainly because that the SPD has a much smaller resistance after being triggered than the characteristic impedance of the cable. The reflection voltage by the cable can be neglected.
2) The 220-V overhead lines are not very long and it can be simplified into a π circuit. The 220-V overhead lines are typically shorter than 100 m, which is quite short in comparison to the wavelength of the surge wave caused by the lightning. Therefore, a π circuit is a reasonable approximation.

A. Reflection Between Transformer and SPD

Various transformer terminal models for high frequency or transient studies have been proposed in literatures [4], [6]–[12], based on forming equivalent linear network, from approximations of impedance or admittance function frequency responses [8]. The purpose of this paper is to get the analytic solution, so the equivalent π-circuit model of the pole transformer in [4] is used, which neglected the inductance branch in the model. The π-circuit model is a simplification of the accurate model, but it still maintains certain accuracy [4]. The circuit between transformer and SPD can be simplified to a circuit as shown in Fig. 2(a). Due to the reflection from these two terminals and the charge and discharge processes of power transformer capacitors, the voltage exhibits periodical oscillation. The SPD along with the grounding resistance leads to the attenuation of the surge voltage, but they do not influence the oscillation period.

Manuscript received February 1, 2011; revised June 25, 2011 and July 25, 2011; accepted August 14, 2011. Date of publication September 26, 2011; date of current version November 18, 2011.

The authors are with the State Key Lab of Power Systems, Department of Electrical Engineering, Tsinghua University, Beijing 100084, China (e-mail: emc2wsc@gmail.com; hejl@tsinghua.edu.cn).

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Digital Object Identifier 10.1109/TEMC.2011.2166119

By neglecting the SPD branch, the circuit can be further simplified into a frequency-domain model as illustrated in Fig. 2(b). The relation of the surge voltage $U_S(s)$ and the voltage $U_x(s)$ can be obtained by solving this circuit:

$$U_x(s) = U_S(s)\,\frac{L_{\mathrm{OL}} C_2 s^2}{L_{\mathrm{OL}}\left(C_2 + C_3 + (C_{\mathrm{OL}}/2)\right)s^2 + 1}. \tag{1}$$

By assuming the voltage source $u_S(t)$ as a step voltage: $u_S(t) = t/\tau_1 \varepsilon(t) - (t - \tau_1)/\tau_1 \varepsilon(t - \tau_1)$, where $\varepsilon(t)$ is Heaviside step function. $u_x(t)$ can be obtained by inverse Laplace transform. Its period T_{TS} is

$$T_{\mathrm{TS}} = 2\pi\sqrt{L_{\mathrm{OL}}\left(C_2 + C_3 + \frac{C_{\mathrm{OL}}}{2}\right)}. \tag{2}$$

On the 220-V overhead lines, the voltage surge has many peaks, which show up periodically. Because the surge wave will be reflected between the SPD and the load, when any of two peaks with the same polarity meet at the load terminal after trips on the cable, the surge voltage wave will be exaggerated.

B. Reflection Between SPD and Load

If the load is a small resistance, a small inductance or a big capacitance, its reflection coefficient is negative, then the longer the cable, the smaller the voltage on protected device. In this scenario, the distance between SPD and load is not an issue. However, if the reflection coefficient of load is positive, voltage exaggeration might happen and there exists a worst distance D_{worst}. Therefore, only the condition of positive reflection coefficient is considered in this paper.

Denote the travelling time between the SPD and the protected device as T_{SL}, it can be obtained by the following formula:

$$T_{\mathrm{SL}} = D_{\mathrm{Cable}}\sqrt{L_{\mathrm{Cable}} C_{\mathrm{Cable}}} \tag{3}$$

where D_{Cable}, L_{Cable}, and C_{Cable} are the length, per unit inductance, and per unit capacitance of the cable, respectively.

If the reflection coefficient of load is positive, the voltage peak comes back to its original position with an opposite polarity after $2T_{\mathrm{SL}}$ seconds' travel on the cable and with the same polarity after $4T_{\mathrm{SL}}$ seconds' travel on the cable. Therefore, if T_{SL} satisfies

$$2T_{\mathrm{SL}} = \frac{T_{\mathrm{TS}}}{2} \tag{4}$$

a positive peak meets the following negative peak after one trip on the cable and the following positive peak after two trips on the cable. Once peaks superpose each other with the same polarity, a higher voltage peak will be generated. Combining (2), (3), and (4) gives

$$D_{\mathrm{worst}} = \frac{\pi\sqrt{L_{\mathrm{OL}}\left(C_2 + C_3 + (C_{\mathrm{OL}}/2)\right)}}{2\sqrt{L_{\mathrm{Cable}} C_{\mathrm{Cable}}}}. \tag{5}$$

When the protected device is D_{worst} far from SPD, it would be subject to the most severe surge voltage.

C. Discussion of the Estimation Formula for Other Load Conditions

For resistive load, the time span between one peak and its reflected peak (denote it as MT_{SL}) is equal to T_{SL}; while if the load is capacitive or inductive, T_{SL} is no longer MT_{SL}. Capacitive load increases the rising time of surge and the value of MT_{SL}, while inductive load decreases the rising time of surge and the value of MT_{SL}. Therefore, D_{worst} becomes smaller in the condition of capacitive load while bigger in the condition of inductive load. For a capacitive load C_{Load}, averaging its value into the per unit capacitance of cable gives

TABLE I
VOLTAGE–CURRENT CHARACTERISTIC OF THE SPD

Voltage (kV)	0.05	0.2	0.5	0.79	1.26
Current (kA)	1×10^{-6}	1×10^{-3}	0.1	1	10

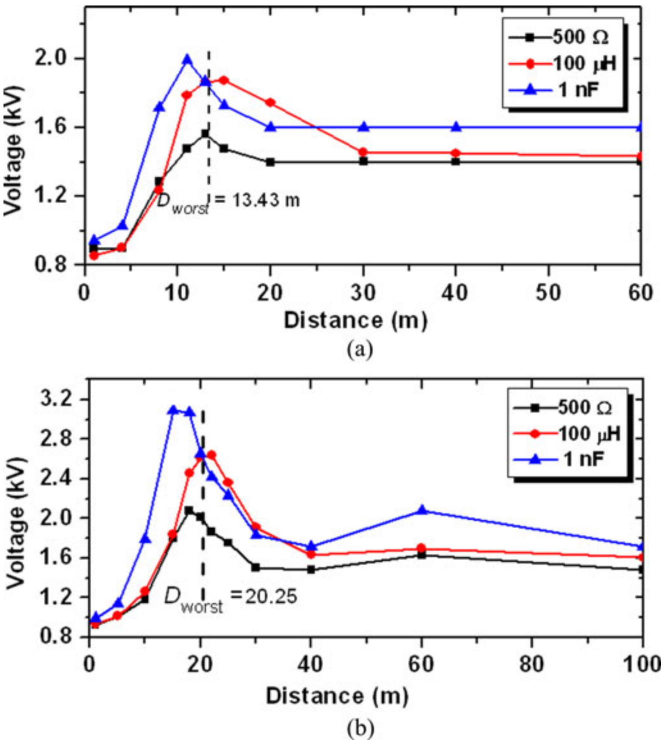

Fig. 3. Peak values of the voltage on the protected device in different conditions. (a) The length of overhead line is 50 m. (b) The length of overhead line is 100 m.

$$MT_{\mathrm{SL}} = D_{\mathrm{Cable}}\sqrt{L_{\mathrm{Cable}}\left(C_{\mathrm{Cable}} + \frac{C_{\mathrm{Load}}}{D_{\mathrm{Cable}}}\right)} \tag{6}$$

and

$$D_{\mathrm{worst}} = \frac{\sqrt{L_{\mathrm{Cable}}^2 C_{\mathrm{Load}}^2 + (T_{\mathrm{TS}}^2/4) L_{\mathrm{Cable}} C_{\mathrm{Cable}}} - 4L_{\mathrm{Cable}} C_{\mathrm{Load}}}{2L_{\mathrm{Cable}} C_{\mathrm{Cable}}}. \tag{7}$$

As for an inductive load, we found that it would not influence MT_{SL} and D_{worst} significantly.

III. CASE STUDY AND RESULTS

Although the deduction above assumes a triangle wave surge voltage as, we will show in this section that the derived formula also has a reasonable accuracy in more realistic scenarios. We used PSCAD as a simulation environment to validate the proposed formula. In the simulation, the 10-kV line is assumed to be 2 km long. Surge arresters are installed on the 10-kV lines every 200 m. A group of surge arresters are installed on the 10-kV side of the transformer. A 20-kA lightning strikes the middle of the line directly. The pole transformer is 200 m from the striking point and the length of 220 V overhead line is adopted as 50 and 100 m. In the transformer model, $C_1 = 120$ pF, $C_2 = 340$ pF, and $C_3 = 1350$ pF. Per unit capacitance and inductance for overhead line are 10.734 pF/m and 1.0361 μH/m, respectively.

Per unit capacitance and inductance for cable are 452.3 pF/m and 3.0685 μH/m, respectively. The voltage–current characteristic of the SPD used in the simulation is given in Table I. The 220-V overhead line is assumed to be perpendicular to the 10-kV lines; therefore, the coupling between them can be neglected.

The corresponding worst distance can be obtained by (5): $D_{\mathrm{worst}} = 13.43$ m for 50-m-long overhead line and $D_{\mathrm{worst}} = 20.25$ m for 100-m-long overhead line. The whole system is simulated in EMTDC; the maximum absolute values of voltage on the protected device are recorded for different distances between the SPD and the load and for different loads, as shown in Fig. 3. When the load is resistive, the estimation of formula (5) has a good agreement with the simulation result. While for inductive and capacitive loads, estimation result is prone to be smaller and larger, respectively. This is consistent with the analysis in Section II.C. When the length of overhead line is 50 m and the value of inductance varies from 50 μH to 10 mH, the relative error of estimated D_{worst} varies from 4.2% to 0.5%; and when the value of capacitor varies from 1 pF to 1 nF, the relative error of estimated D_{worst} obtained by (5) varies from 0.2% to 13%, while the relative error of (7) varies from 0.2% to 6%. When the length of overhead line is 100 and 200 m, the maximum relative error of the estimation formula are 9% and 11%, respectively. Therefore, in the design of lightning protection for low-voltage network, it should be avoided that the protected device is separated from the SPD by D_{worst}.

IV. CONCLUSION

It is commonly known that the longer the distance between an SPD and a protected device, the worse the protection effectiveness of the SPD. We have shown in this paper that this is not true for low-voltage power circuits due to the special circuit topology. There exists a worst distance between SPD and protected device. An analytical formula to estimate the worst distance between the protected device and the SPD is presented in this letter when the coupling between 10 kV and 220 V lines is neglected, the results given by this formula has a good agreement with the simulation ones of EMTDC when the length of overhead line is not very long.

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On Inductance of Buried Horizontal Bare Conductors

L. Grcev, B. Markovski, and S. Grceva

***Abstract*—External inductance is one of the basic quantities in the classical approach to the surge and high-frequency analysis of buried horizontal bare conductors. However, there is no consensus, in the modern literature, on the treatment of the effects of the earth surface in the approximate expressions for the inductance, and several different formulas are often used. In this paper, we derive a new expression for the external inductance of buried horizontal conductors that accurately takes into account the effects of the earth surface and compare the errors of the usual approximate formulas. We also propose new approximate formulas that lead to smaller errors for depths of burial less than or equal to 1 m.**

***Index Terms*—Circuit modeling, distributed parameter circuits, grounding electrodes, lightning, transmission line modeling.**

I. INTRODUCTION

High-Frequency and surge modeling of buried horizontal conductors is of interest for a variety of electromagnetic compatibility and lightning-related studies [1]. One of the classical approaches to modeling is a representation of the conductor by a transmission line with uniformly distributed parameters [2]. A simple method to approximately estimate the required unit length parameters was suggested by Sunde (see [2, p. 256]). The leakage conductance, external inductance, and capacitance of the finite-length conductors were first derived from static (dc) conditions. Then, their values were divided by the conductor length, yielding the approximate unit length parameters. This approximate method is still very popular and was recently compared with other methods for high-frequency and surge analysis of grounding electrodes [3].

However, there is no consensus in the modern literature on the treatment of the effects of the earth surface in the approximate expression for the external inductance, and several different formulas (in which the effects of the earth surface are either completely neglected or treated by

Manuscript received February 24, 2011; revised June 4, 2011; accepted August 1, 2011. Date of publication September 15, 2011; date of current version November 18, 2011. This work was supported in part by the Republic of Macedonia, Ministry of Education and Science and in part by the Macedonian Academy of Sciences and Arts.

L. Grcev is with the Macedonian Academy of Sciences and Arts, Skopje 1000, Macedonia, and also with the Faculty of Electrical Engineering and Information Technologies, Ss. Cyril and Methodius University, Skopje 1000, Macedonia (e-mail: Leonid.Grcev@ieee.org).

B. Markovski is with the Faculty of Electrical Engineering and Information Technologies, Ss. Cyril and Methodius University, Skopje 1000, Macedonia (e-mail: bmarkovski@feit.ukim.edu.mk).

S. Grceva is with the Faculty of Information and Communication Technology, FON University, Skopje 1000, Macedonia (e-mail: Solza.Grceva@fon.edu.mk).

Digital Object Identifier 10.1109/TEMC.2011.2165340