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By

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ANALYSIS OF TRAVELING WAVES IN UNDERGROUND CABLES

Edvard Hoefler

Analytical papers on this problem to date are mainly related to over-voltage shock with a vertical or steep front and an infinitely long crest. This article analyzes the form of over-voltage in underground cables for a wave with a vertical front and a falling crest (which is closer to the real conditions). The derived expression enables an estimate of the voltage in the cable as a function of time for any length of cable and duration of the over-voltage wave. The shorter the cable the more accurate the calculation. Figures show over-voltages in cables between two power lines and between a power line and a transformer (assuming certain wave resistances).

Introduction

Among networks which are exposed to atmospheric over-voltages, underground cables of relatively short lengths represent a particularly sensitive element. This is understandable when we take into consideration that wave resistance changes at each end of the cable and that this causes refraction and reflection of waves. The consequences of this are changes in voltage and current of traveling waves which can, under certain conditions, endanger the insulation of the cable and the connecting equipment.

Generally, an underground cable having a wave resistance Z_2 is in practice placed between two other elements of the network with their body resistance Z_1 and Z_3. On the basis of known rules about refraction and reflection of traveling waves, we must include the following factors in the calculation:

-- For a wave that enters at the beginning of the cable (point A in Fig. 1)

$$a_{12} = \frac{2Z_2}{Z_1 + Z_2} \qquad (1)$$

-- For a wave that is leaving the cable at the end (point B in Fig. 1)

$$a_{23} = \frac{2Z_3}{Z_1 + Z_3} \qquad (2)$$

-- For a wave in the cable that is reflected back into the cable:

at point A: $b_{21} + \frac{Z_1 - Z_2}{Z_1 + Z_2}$ (3)

at point B: $b_{23} = \frac{Z_3 - Z_2}{Z_2 + Z_3}$ (4)

When an over-voltage wave appears at the beginning of the cable (point A in Fig. 1) with a vertical front of height U_o and with a flat infinitely long crest ($T = \infty$), then at the other end of the cable (at point B after a sufficient number of oscillations) there will appear (neglecting losses) a voltage of magnitude [1].

$$U_B = U_0 a_{12} a_{23} \frac{1}{1 - b_{21} b_{23}} \qquad (5)$$

If, in diffraction and reflection, we introduce factors corresponding to expressions from equations (1) to (4), we obtain

$$U_B = U_0 \frac{2Z_3}{Z_1 + Z_3} \qquad (6)$$

In the case where a cable lies between two power lines, $Z_1 = Z_3$ and the voltage at the end B is

$$U_B = U_0 \qquad (7)$$

In the case where the cable lies between a power line and a transformer $Z_3 \gg Z_1$, the voltage at the end B approximates twice the value of U_0. For $Z_3 = \infty$ (cable at the end B is disconnected, then

$$U_A = 2U_0 \qquad (8)$$

In this case the voltage at the end of the cable is twice as large as that at its beginning. It is understood that practically the same over-voltage should also appear at the beginning of the cable. However, at that point, conductors are always connected, keeping the over-voltage at the beginning of the cable at a certain level.

The well-known directive that derives from this construction is that in this case the cable must be protected by over-voltage conductors at both ends, i.e., at the transition from the power line to the cable and at the transformer. An exception to this are very short cables where the conductor protective zone also includes the other end of the cable. Related information can be found in new directives for coordination of insulation [2].

However, the over-voltage waves with an infinitely long crest do not exist. As in case of a lightning shock, each over-voltage shock has a given length. Because the end is very indeterminative, it is practical to express the length of the over-voltage wave by the time that it takes for it to drop to 50% of its peak value. There are numerous statistical data for this parameter. According to the newest information [3], the duration of the first negative partial lightning shock corresponds to

over 30 μs in 95% of the cases
over 75 μs in 50% of the cases
over 200 μs in 5% of the cases

For calculations, we can thus use 60 μs for total duration of the over-voltage wave (as an average) for 95% of all cases.

In relation to this, it is of interest to find the voltage at the end of the cable when an overvoltage wave has a falling crest with a given duration of T μs. Can we also expect over-voltages in this case with values presented above for a wave with the infinite duration of its crest? What is the form and peak value of the voltage at the other end of the cable? Is it also necessary to apply over-voltage conductors at both ends of the cable?

These questions will be answered by the analysis presented in the following chapter.

New analysis of over-voltage in a cable

For the purpose of analysis, we will divide the over-voltage wave U_o at the entrance of the cable into equal parts with duration τ (μs) and with a dropping peak value as shown in Fig. 1. An analysis of the condition was carried out earlier [4]. However, it was done under somewhat different assumptions and for the case of a cable between two power lines. The idea used there is further developed here and expanded to enable equations of general validity to be applicable to all possible cases in practice.

As may be observed in Fig. 1, the wave is divided into partial shocks of duration τ which is assumed to correspond to twice the time required for the wave to travel through a cable of length L. Thus

$$\tau = \frac{2L}{v} \mu s, \quad (9)$$

where "L" is the length of the cable in meters and "ν" is the traveling velocity of the wave in the cable in m/μs.

Accordingly, a wave with a crest duration T (μs) consists of N partial waves where

$$N = \frac{T}{\tau} = \frac{vT}{2L} \quad (10)$$

In order to approximate the real form of a wave with a falling crest, each subsequent partial wave is lower than the preceding one by ΔU_o. According to this

$$U_0 = N \Delta U_0 \quad (11)$$

and

$$\Delta U_0 = \frac{U_0}{N} \quad (12)$$

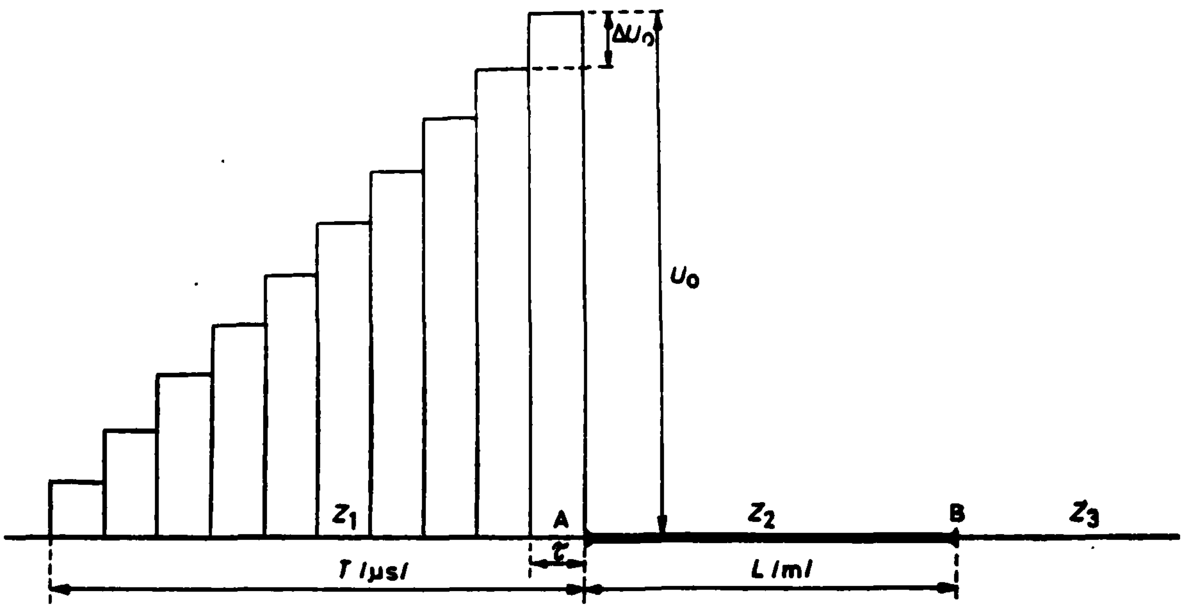

Fig. 1. Schematic illustration of an over-voltage wave with a falling crest, composed of partial waves of duration τ.

The following voltages appear at the end B for individual time periods τ:

$$t = 0:\ U_B = 0$$

$$t = \tau:\ U_B = U_0 a_{12} a_{23}$$

$$t = 2\tau:\ U_B = (U_0 - \Delta U_0) a_{12} a_{23} + U_0 a_{12} a_{23} b_{21} b_{23}$$

$$t = 3\tau:\ U_B = (U_0 - 2\Delta U_0) a_{12} a_{23} + (U_0 - \Delta U_0) a_{12} a_{23} b_{21} b_{23} + U_0 a_{12} a_{23} b_{21}^2 b_{23}^2$$

$$t = n\tau:\ U_B = /U_0 - (n-1)\Delta U_0/ a_{12} a_{23} + /U_0 - (n-2)\Delta U_0/ a_{12} a_{23} b_{21} b_{23} + (U - \Delta U_0) a_{12} a_{23} b_{21}^{n-2} b_{23}^{n-2} + U_0 a_{12} a_{23} b_{21}^{n-1} b_{23}^{n-1}$$

In order to simplify the expressions, we introduce the following relations:

$$a = a_{12}\, a_{21} \qquad b = b_{1}\, b_{2}$$

Besides, we can exchange (illegible) with U_0N and we obtain

$$\frac{U}{U_0} \ldots (1 - \frac{n-1}{N}) a \ldots (1 - \frac{n-2}{N}) a b \tag{13}$$

$$\ldots (1 - \frac{n-3}{N}) a b^2 \ldots (1 - \frac{2}{N}) a b^{n-3} \ldots (1 - \frac{1}{N}) a b^{n-2} \ldots a b^{n-1} \tag{14}$$

By further rearrangement of the members, we obtain

$$\frac{U_B}{U_0} = a(1 + b + b^2 + \ldots b^{n-1}) - \frac{a}{N}[n(1 + b + b^2 + \ldots b^{n-2}) - (1 + 2b + 3b^2 + \ldots + (n-2) b^{n-3} + (n-1) b^{n-2})] \tag{15}$$

Because b is always smaller than 1, we can replace the first two rows by a sum and the third row can be derived from the series $(b + b^2 + b^3 + \ldots b^{n-2} + b^{n-1})$.

Accordingly,

$$\frac{U_B}{U_0} = a \frac{1-b^n}{1-b} - \frac{a}{N}\left(\frac{n(1-b^{n-1})}{1-b} - \left(\frac{b-b^n}{1-b}\right)\right) \tag{16}$$

and finally

$$\frac{U_B}{U_0} = a\left(\frac{1-b^n}{1-b} - \frac{b^n + n(1-b) - 1}{N(1-b)^2}\right) \tag{17}$$

The expression by equation (17) enables us to determine relative value of the voltage at the B end of the cable as a function on the number n of completed double passages through the cable. When the number n reaches the value of N, the external factors disappear and the equation (17) is no longer applicable. The voltage which, at the moment, still remains in the cable decreases to the vanishing point by further oscillations between both ends of the cable.

The examples listed below demonstrate practical application of equation (17). We assume the following wave resistances:

For the power line	500 Ω
For the cable	50 Ω
For the transformer	5000 Ω

Cable between two power lines

On the basis of the above-listed wave resistances, we obtain the following factors for diffraction and reflection:

$$a_{12} = 0{,}182 \qquad a_{21} = 1{,}818 \qquad a = 0{,}327$$
$$b_{21} = 0{,}818 \qquad b_{12} = 0{,}818 \qquad b = 0{,}67$$

Using these factors, the ratio U_B/U_o was calculated as a function of "n" by equation (17) for the following values of N:

N = 5, 10, 20, 50, 100 and 1000

The results are illustrated in the form of a diagram in Fig. 2. It can be immediately recognized that the voltage U_B does not reach the value of U_o except in the case when $T = \infty$, which is identical to the already-described case. If we accept that the length of the wave "T" is more or less constant and that the velocity of the wave in the cable is "v", then the over-voltage at the B end of the cable becomes larger when the length of the cable is decreased.

The curves in Fig. 2 show, at the same time, the form of the over-voltage because the number of double passages through the cable increases with time. We observe, as was noted in the mentioned report, that starting with an initial wave with a vertical front and an evenly falling crest, we arrive at a wave with a relatively long front and an even longer crest. The way this appears in practice is shown by the following example (used from reference [4]):

Cable length	$L = 500$ m
Wavelength	$T = 100$ μs
Velocity	$\nu = 100$ m/μs

$$N = \frac{\nu T}{2L} = \frac{100 \times 100}{2 \times 500} = 10$$

(This number, in the report, corresponds to n = 20.)

From the diagram in Fig. 2, the highest relative voltage corresponds to

$$U_B \; U_0 = 0{,}63$$

(In the report, the value obtained was $U_2/U_o = 0.61$.)

The front length is

$$t_1 = 4\tau = \frac{4 \times 2L}{\nu} = 40\ \mu s$$

The wavelength evaluated from the diagram for $15\tau = 150$ μs.

When the selected parameters for N fall between 5 and 1000, we can use the diagram in Fig. 2 to evaluate the highest voltage at the B end as well as the form of the voltage for any case. By use of the obtained results, we can estimate the expected voltage load for the connecting equipment as well, and make a proper selection of voltage conductors if they are necessary.

Cable between the power line and the transformer

In this case, the following factors are applied for refraction and reflection:

$$a_{12} = 0,18 \qquad a_{23} = 1,98 \qquad a = 0,356$$
$$b_{21} = 0,818 \qquad b_{23} = 0,98 \qquad b = 0,8$$

For the case "N" values, we obtain (as in the previous example) the relative voltage at the B end, using equation (17). These can be determined by using the diagram in Fig. 3. The largest value for U_B U_o in Fig. 3 corresponds to 1.74 and is smaller than one for a wave with an infinitely long crest, and which is derived from equation (6). Thus, with wave resistances of

$$Z_1 = 500\ \Omega \qquad Z_2 = 50\ \Omega \qquad Z_3 = 5000\ \Omega$$

we obtain from equation (6)

$$U_B/U_o = \frac{2 \times 5000}{5500} = 1,82$$

However, the curve for N = 1000 in Fig. 3 applies to the cable of length L=5m (using T=100μs and ν = 100 m(μs). For a cable 50 m long and the same values for T and ν, we have

$$N = \frac{100 \times 100}{100} \quad 100$$

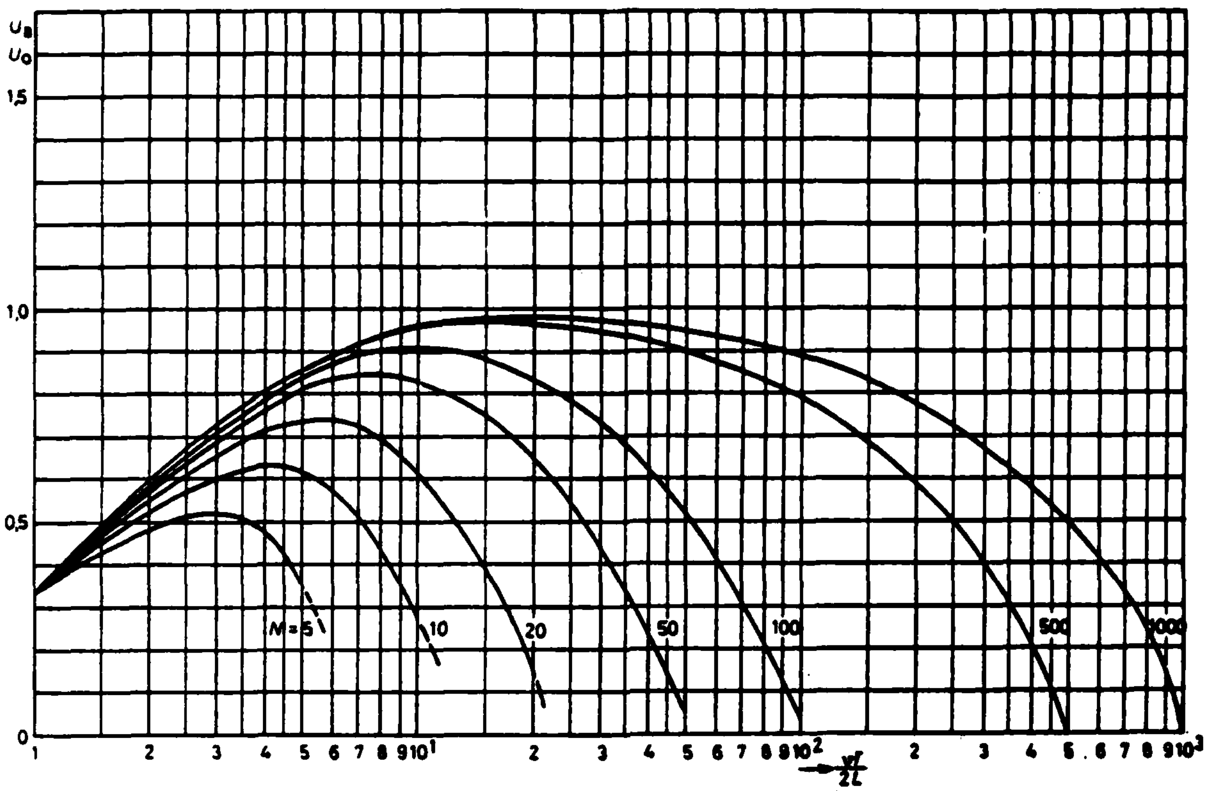

Fig. 2. Relative over-voltage U_B/U_o at the B end of a cable as a function of the number n (double passages through the cable) for various values of the parameter N. Example applies to a cable between two power lines.

and the highest relative voltage at the B end is 1.53.

For given parameters of T and ν, the curves in Fig. 3 cover the cable lengths from 5 to 1000 m. It is understood that other cable lengths would be obtained for different T and ν parameters. In summary, the curves in Fig. 3 enable determination of relations between voltages U_B/U_o for the area which covers all practical examples.

For wave resistances which deviate from those accepted above, all possible cases can be calculated using equation (17).

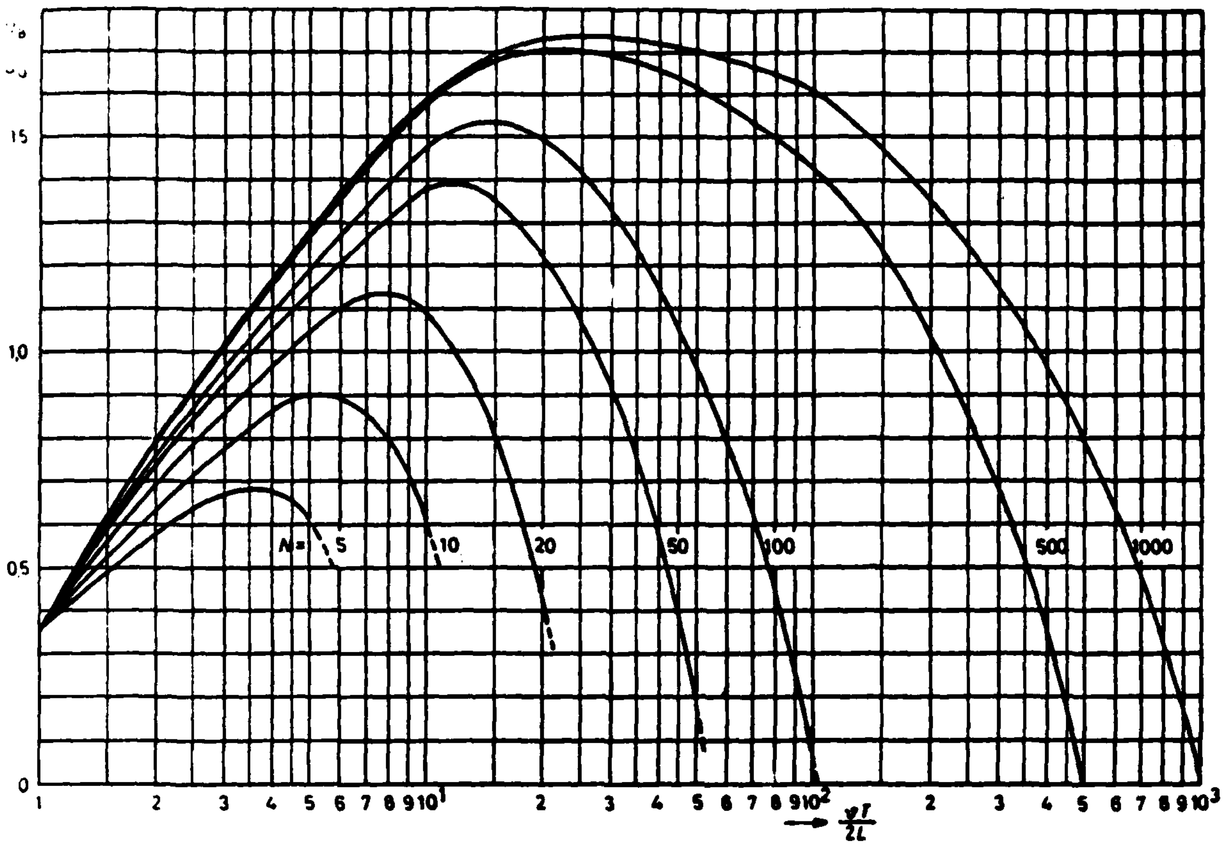

Fig. 3. Relative over-voltage U_B/U_o at the B end (at the transformer) as a function of the number n (double passages through the cable) for various values of parameter N. This example applies to a cable between a power line and a transformer.

Conclusion

The above analysis enables an estimate over the over-voltage value at the end of a cable of length L when at its beginning there appears an over-voltage of a value U_o. For known wave resistances and velocities of waves in the cable, the actual values are a function of the accepted length for the over-voltage wave T (μs). As a safety factor, the assumed length should be longer than standard. According to the above-mentioned statistics [3] , only 5% of all negative lightning shocks (first reversed shock) have halving value in excess of

200 μs. Thus, to cover 95% of probable cases, we can use $T = 400\ \mu s$ in calculations (approximately). For a cable with $v = 100\ m/\mu s$ we obtain

$$L\,N = \frac{100 \times 400}{2} = 20\,000.$$

This means that in the case of a cable at a transformer, voltage U_B at the end will not exceed voltage U_1 at the beginning (with 95% probability) for all cables where $N < 15$ (approximately) or

$$L > \frac{20\,000}{15} = 1\,333\ \text{m}.$$

Because such lengths of cables are very rare, it follows that over-voltage conductors must be installed at both ends of the cable in almost all cases.

This conclusion is also valid for a cable between two power lines, because there is the possibility of an over-voltage wave occurring at either end of the cable. The over-voltage must be conducted away because of limited capability of cable carriers to withstand over-voltage shocks.

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