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Lightning impulse efficiency of horizontal earthings

Abstract *Earthings of the electrical power systems can achieve wide sizes. Due to equipotential connections and a presence of main equipotential bar the earthing system can be connected even to a power transformer neutral point. Evaluation of such wide earthings for lightning protection purposes cannot be easy to perform because only a part of the earthing system is useful. This useful part of the earthing is described as its effective length. The paper deals with the methods of effective length calculations and measurement results performed using computer simulations, analogue models and real earthing tests. Lightning impulses of 1, 4 and 10 μs front times have been taken into account. A good convergence of investigation results has been obtained.*

Streszczenie *System uziemień współczesnych obiektów jest zwykle bardzo rozległy, a łączenie poszczególnych elementów uziemiających za pomocą głównej szyny wyrównania potencjałów uwzględnia także uziemienia stacji transformatorowej. Ocena przydatności takiego systemu do celów ochrony odgromowej nie jest prosta, bo tylko jego część określana, jako długość efektywna bierze udział w odprowadzaniu do gruntu prądu piorunowego. Praca zawiera rezultaty obliczeń długości efektywnej uziomów, wyniki symulacji komputerowych, pomiarów na modelach analogowych, a także na rzeczywistych uziomach poziomych. W badaniach stosowano udary o czasach czoła 1, 4 i 10 μs. Uzyskano dobrą zgodność rezultatów obliczeń i symulacji z wynikami pomiarów na obiektach rzeczywistych (**Piorunowa efektywna długość uziomów poziomych**).*

Keywords: lightning protection earthing, earthing impulse impedance, effective length of earthing.
Słowa kluczowe: uziemienia odgromowe, udarowa impedancja uziemień, długość efektywna uziemień.

Introduction

Ground electrodes are important and necessary lightning protection elements of any building structure as well as of any power energy system. Dispersion of lightning currents to a surrounding soil is their basic function. Properly designed and constructed earthing guarantees safety for both people and devices located in places where a flow of dangerous surge current caused by a lightning discharge can occur. Earthing systems for the lightning protection purposes should be characterized by a small voltage drop across what when the lightning current is carried away to the ground. Therefore, the earthing resistance or impedance should be made as low as possible and its value should meet the guidelines contained in the specified standards and regulations, for example a value of 10 Ω can be often found [1].

Requirements of low resistance in impulse conditions cannot be realized by extension and enlarging of buried ground wires as is broadly practised in the case of service earthing. Service earthings provide for carrying away of short circuit currents about network frequencies, and they work in the domain of courses of about millisecond durations. Too wide earthing is not able to protect objects at lightning currents. Consideration of the time constant of earthings and current wave velocity shows that enlarging of earthing size is effective only to a certain value and this value is called effective length [2, 3].

Paper presented the investigation results of impulse current carrying away to a surrounding ground by particular segments of a long horizontal earthing. Current impulses of 1, 4 and 10 μs front times were taken into account. The investigations have been performed using computer simulations and analogue models as well as real earthings. The work gives also some advice concerning a problem what part of a total impulse current is carried away to a ground by the effective length of an earthing.

Effective length calculations of earthing electrodes

According to Szpor, increasing a length of earthing electrode is effective until a time constant of the electrode is not bigger than a front time of an impulse at an electrode feed point. So the maximum useful length of earthing electrode called as an effective length can be found from the following formula [4]:

$$l_{eff} = \frac{\pi}{2}\sqrt{\frac{T}{GL}} \tag{1}$$

where: T denotes a rise time of a supplying impulse, L - inductance per length unit and G – conductance per length unit of the electrode.

New formulas for the effective length of grounding electrodes have recently been proposed by Grcev [6]. These formulas are applicable for an analysis, when an influence of ionisation in a ground surrounding an earthing bar is ignored - the same assumption was taken for the previous formula. The effective length (in meters) is determined by [5]:

$$l_{eff} = \frac{1-\beta}{\alpha} \tag{2}$$

In order to find the effective length of an earthing, the coefficients α and β should be computed as:

$$\alpha = 0.025 + \exp[-0.82(\rho T)^{0.257}] \tag{3}$$

$$\beta = 0.17 + \exp[-0.22(\rho T)^{0.555}] \tag{4}$$

where: the soil resistivity ρ is expressed in Ωm and T denotes the front time of a current impulse in μs. Coefficients α and β do not have any physical meaning and they are deduced from computer simulations by using the EM model.

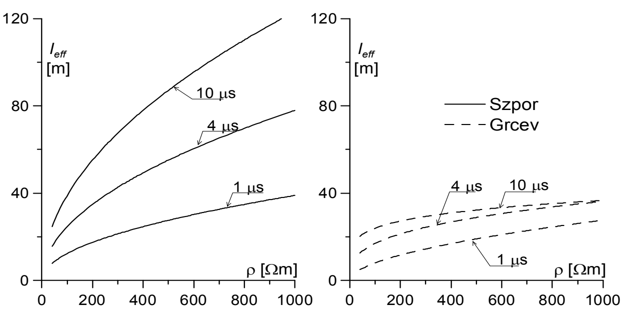

Fig. 1. Effective length of earthing electrodes versus soil resistivity calculated according to Szpor - continuous line and Grcev - dashed line.

Fig. 1 presents calculation results of the effective lengths according to formulas (1) and (2) versus soil resistivity for impulses of 1, 4 and 10 μs front times. One can see that in the resistivity range of about 40 - 100 Ωm both formulas provide similar values of calculated effective lengths of earthings. For higher resistivity grounds the effective length according to Szpor method seems to be much higher than that of Grcev. Curves obtained from the second formula are characterized by a trend to be stabilized for higher soil resistivity of a range of hundreds Ωm.

Computer simulations and model measurements

Due to the nature of the electrical voltages and currents in earthing, a usual line model has been applied for a horizontal earthing. In the model, parameters per length unit are described as resistance *R*, inductance *L*, capacity to earth *C* and conductance *G*. Those lumped parameters were calculated in the way proposed by Verma and Mukhedkar [6]. Computer simulations were performed using Matlab - Simuling package and basic segment of a horizontal earthing model was 2 m long. The main aim of the investigation was the measurement of low frequency resistance *R* and impedance *Z* at impulses 1, 4 and 10 μs front times of the earthing model. The model was extended to 50 m and computer measurements were repeated with a step of 2 m. The results of the investigations are presented in Fig. 2. Values of an impedance Z have been calculated according to the standard 62305 as "a ratio of maximum values of voltage drop and current, which usually are not at the same time" [1]. The proper curves of effective lengths calculated from formulas (1) and (2) have been marked i.e. according to Szpor and Grcev respectively.

Effective lengths proposed by Grcev are determined for the following assumption:

$$k_i = \frac{Z}{R} = 1 \tag{5}$$

where k_i denotes an impulse coefficient of an earthing, *R* - a low frequency resistance of an earthing and *Z* - its impulse impedance. So for $l \leq l_{eff}$ low frequency resistance of the earthing is equal to its impulse impedance. When the length of an earthing is longer than its effective length, an earthing impedance becomes higher than its resistance, what can be seen in Fig. 2.

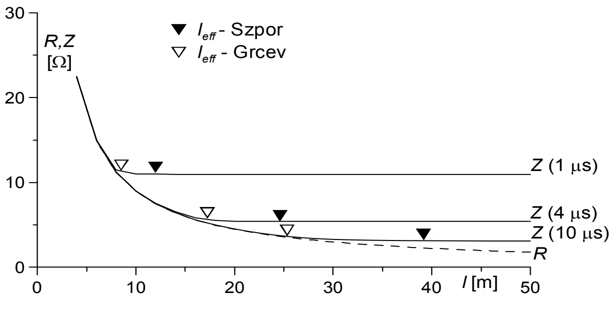

Fig.2. Low frequency resistance R and impedances Z from computer simulations at impulses of 1, 4 and 10 μs front times for horizontal earthing buried in 100 Ωm soil versus length of the earthing; effective lengths of earthing according Szpor and Grcev have been marked on curves

In order to verify formula (1) proposed by Szpor a mentioned above computer model of a 50 m horizontal earthing buried in a soil of 100 Ωm was divided into 10 segments each of 5 m. During computer simulations different impulse currents were recorded as can be seen in Fig. 3a. A curve described as 0 denotes a current of 1 μs front time injected to the model at the feed point, a curve 1 - a current dispersed to earth by the first segment of the model (0 - 5 m), a curve 2 - a current dispersed by the third segment (10 - 15 m) and a curve 3 - a current dispersed by the sixth segment (25 - 30 m). All the currents are expressed in % because the current injected at the feed point has been treated as the reference one and its maximum value has been assumed as 100%. The meaning of the effective length is illustrated by the front times of dispersed currents 1, 2 and 3 in Fig 3a. In Fig. 3b results of analogue model measurements made for the same assumptions like for computer simulations described above have been presented. It shows good similarity of results obtained for both investigation methods.

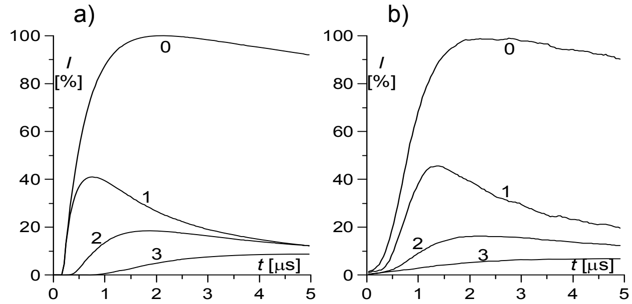

Fig. 3. Impulse currents of an 50 m long horizontal earthing versus time obtained from computer simulations - a and from analogue model measurements - b; 0 - current of 1 μs front time injected at feed point, 1 - current dispersed to earth by segment 0-5m, 2 - current dispersed by segment 10-15 m, 3 - current dispersed by segment 25-30 m

The front times of the particular segment currents increase when a distance between the feed point and the analysed segment increases. A curve described as 2 represents a current dispersed to earth by a segment referring to a distance of 10 - 15 m. This distance is approximated to an effective length of the earthing equal to about 14 m so its front time is similar to that of the injected current - 1 μs. The front times of the currents carried away to earth by segments far from the feed point seem to be longer than the front of the injected one.

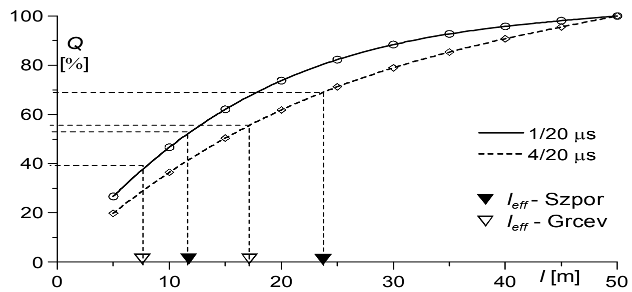

Fig.4. Charge expressed in percentage of the injected one dispersed by a horizontal earthing to a ground versus segment position along the earthing, uninterrupted line refers to 1 μs impulse, dashed line - to impulse of 4 μs; effective lengths for relevant impulses according to Szpor and Grcev have been marked on curves

In order to check the meaning of particular segments of a horizontal earthing in dispersion of lightning discharge currents to a surrounding ground, a total charge carried away by each earthing segment was evaluated. A segment charge was calculated as a time integral of a proper current obtained from computer simulations and shown in Fig. 3a. Results of such calculations have been presented in Fig. 4.

An uninterrupted line refers to impulse currents of 1 μs front time and a dashed one - to currents of 4 μs. A participation of an effective length of an earthing in charge dissipation in a soil depends on a ratio of an injected impulse front time and its half value time. The half value times of both current impulses in presented simulations were kept on the same level of about 20 μs. Curves in Fig.4 show that an effective length calculated according to Szpor disperses about 50 - 70% of the total injected charge and an effective length determined according to Grcev - 40 - 60% of the total charge.

Test results of a real earthing

Computer simulation and model measurement results described above have been verified and compared with the test results performed on a real horizontal earthing. The earthing consisted of a 4x25 mm zinc coated flat iron and it was buried 0,5 m deep in a soil of about 85 Ωm resistivity. The earthing was 50 m long and was divided into 10 segments each of 5 m. The separate segments could be connected in series above a ground surface. Measurement results of low frequency resistance and impedances at 1, 4 and 10 μs for different lengths of the earthing have been presented in Fig. 5. Generally, the shape of proper curves seems to be similar to those obtained for computer simulations and presented in Fig.2. However, it can be stated that a bit higher value of an effective length calculated according to Szpor affords possibilities for better designs of earthings. Small disturbances noticeable on curves are probably caused by too big step of length changes (5 m) during measurements.

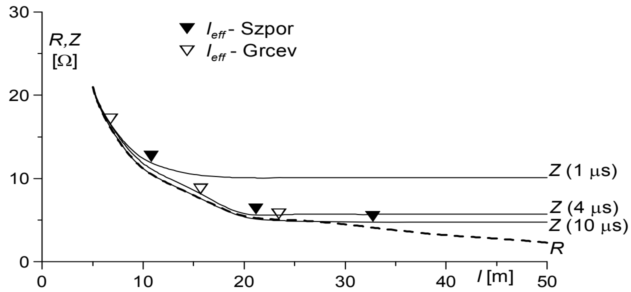

Fig. 5. Low frequency resistance R and impedances Z measured at impulses of 1, 4 and 10 μs front times for real horizontal earthing buried in 85 Ωm soil versus length of the earthing; effective lengths of earthing according Szpor and Grcev have been marked on curves

An influence of an earting length on lightning surge values can be discussed on the ground of voltages and currents recorded at the feed point of the tested earthing and presented in Fig.6 and 7. Voltage courses in Fig 6a and b indicate that an additional 10 m long segment placed below an effective length of a horizontal earthing is able to reduce a voltage at the feed point by more than 2 times.

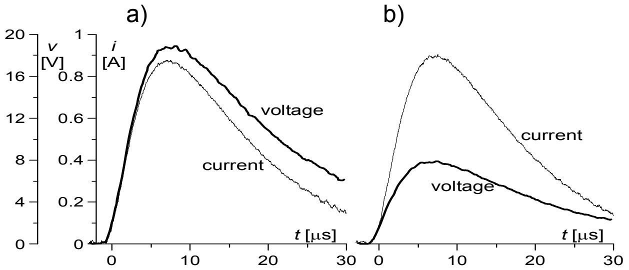

Fig. 6. An influence of a real earthing elongation for a range of $l<l_{eff}$ on time current and voltage characteristics at an earthing feed point; a - $l=5$ m, b- $l=15$ m.

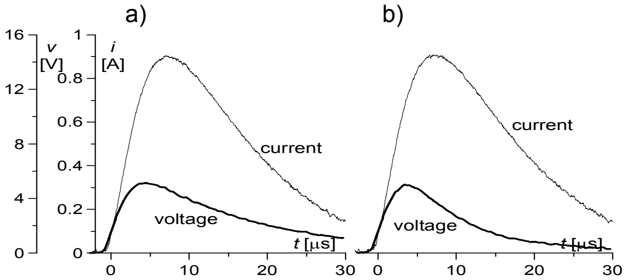

Fig. 7. An influence of a real earthing elongation for a range of $l>l_{eff}$ on time current and voltage characteristics at an earthing feed point; a - $l=20$ m, b- $l=30$ m.

Fig. 7a and b show that the same 10m long segment added to an horizontal earthing beyond its effective length, here between the 20-th and 30-th meter, does not reduce a maximum value of voltage at the feed point of the earthing. So an extension of a horizontal earthing beyond its effective length has no influence on a voltage at a place of a current injection.

Conclusions

Front times of currents carried away to a ground by particular segments of a long horizontal earthing increase with a distance from a feed point and a current dispersed by a segment located at effective length has a front time equal to that of an injected current.

Currents carried away to a soil by segments placed from a feed point in a distance lower than an effective length of the earthing reduce a maximum surge voltage at the feed point. Currents carried away by earthing segments beyond an effective length have no influence on the maximum voltage at the feed point, but they reduce tail values of the surge voltage and dissipate a part of a charge injected to the earthing at its feed point.

According to the computer simulations and real measurements described above, a participation of an effective length in dispersion of an injected charge can change in a range of 30 to even 70%.

The effective length according to Szpor seems to have a bit higher value than that calculated by Grcev's method, especially for higher values of a ground resistivity. As a result of measurements performed for real earthing buried in low resistivity ground it can be stated that Szpor's method affords possibilities for better designs of earthings.

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