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Coupling Effect in Substation Ground Measurements

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Abstract: A method to measure ground impedance in various soil structures is described, which takes into account inductive coupling between current and potential wires. For this purpose, a family of coupling effect curves versus the potential wire length was calculated. It was found that these curves are not dependent on the current wire length and are practically identical to the same soil resistivity. The true resistance of the substation grounding is determined using received coupling effect curves, and a simple formula which subtracts the coupling effect from the measured substation grounding resistance. Practical comparative measurements were performed to validate the method.

Keywords: Coupling effect, Ground impedance, Impedance measurement, Soil resistivity, Substation.

1 Introduction

The development of modern extra-high voltage power systems demands higher safety, stability and economic operation. A good grounding system is required to maintain safe operation. The main datum characterizing a grounding system is its resistance to earth.

There are several methods for measuring grounding system resistance. Among them, the fall-of-potential method is most widely applied for almost all types grounding systems, as proven in many field tests [1, 2].

In order to measure the ground resistance of a substation, it is necessary to apply a voltage between the substation grounding system and the remote (current) electrode that causes the circulation of a current through it. A potential electrode is placed at various positions between the current electrode and the grounding system. The measurement device is connected to the current and the potential electrodes with current and potential wires.

The ratio of voltage to current, known as the apparent resistance, is plotted against the distance from the substation. The required value of the grounding system resistance is located on the resultant curve in the vicinity of a point matching potential wire length (0.5 – 0.7 of the current wire length).

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The measured voltage consists of two components: 1) the actual voltage difference between the grounding system under test and the potential electrode, and 2) the inducted potential due to alternating current flowing in the current test loop. This component – the inducted potential – is called the "coupling effect" [3].

The position of the potential electrode with regard to the current electrode may differ. The method frequently used by testers is situating the electrode wires with 90º between them. The clear advantage of this method is the lack of the coupling effect. The disadvantage lies in the impossibility of controlling underground conducting objects. For example, a steel pipe lying underground parallel to the potential wire reduces the measured voltage without distorting the shape of the curve. Positioning the current and potential electrodes at opposite sides of the substation does not eliminate the coupling effect which is due to the return to the grounding current, and does not allow for the discovery of conducting objects in the ground.

Positioning the potential electrode in line with the current electrode enables detection of various objects in the ground – water pipes, large metal bodies, etc. An insert will deform the shape of the curve. When the deformed curve is obtained during measurements, the testing technician selects another direction from the substation to perform the measurement, thereby reducing the inaccuracy in the measurement results. However, due to the above described coupling effect, the results will be higher than the actual grounding resistance value.

Modern substations are usually located in the built up zones. Therefore it is difficult or impossible to find more than one direction free of transmission lines, buildings or underground communications to spread the measuring wires. In this situation, when the current and potential wires are spread in one direction, it is necessary to take into account the coupling effect. Otherwise, accuracy of measurement will be low.

Carson, in his widely known paper [4], defines the mutual impedance between two infinite wires located above a homogeneous earth. Subsequently, Foster [5] gives an expression for calculating the mutual impedance between two insulated wires lying on the earth's surface, of finite length, negligible diameter and grounded at their end-points. Calculations of the coupling effect described in various proceedings are labour-consuming for each concrete substation [3, 6 – 8]. The simplified formulas offered in these proceedings often have restrictions preventing applying them in all cases. Today there are no simple methods to calculate substation ground resistance from field measurements that take into account the coupling effect.

The purpose of this work is to develop a uniform technique to measure the substation ground resistance which considers the coupling effect. At the same time, the technique should encourage avoidance of labor-consuming calculations.

2 Analytical Survey

During the substation ground measurement, both wires – current ***C*** and potential ***P*** – are lying on the surface with the distance ***Y*** between them (Fig. 1). Current ***I*** flows in the horizontal conductor and returns through the earth. Both these currents induce parasite electromagnetic forces in the potential wire.

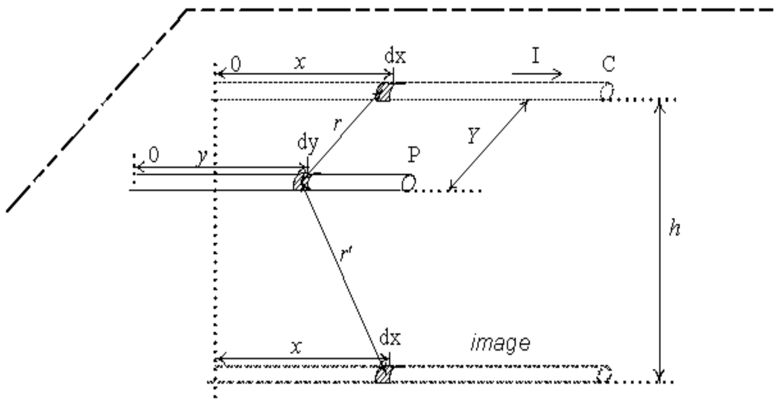

Fig. 1 – *Mutual coupling between parallel conductors* C – *current wire*, P – *potential wire*, *image – image conductor for return current.*

Return current flow in the earth can be modeled by a perfect conducting plane, an image conductor, which is located at a complex depth *h* below the earth's surface. The concept of replacing earth with a conductive plane located at a complex distance below the earth's surface appears in A. Deri et al. [9]:

$$h = \sqrt{\frac{\rho}{\mathrm{j} w \mu_0}} = (1-\mathrm{j})\frac{10^3\sqrt{10}}{4\pi}\sqrt{\frac{\rho}{f}}, \tag{1}$$

where:

μ_0 – magnetic constant, $4\pi \cdot 10^{-7}$ H/m;

w – angular frequency, $w = 2\pi f$;

ρ – soil resistivity;

f – test current frequency.

A closed loop formed by the source, current wire, current electrode and image wire (a straight horizontal line in the earth). Current from this closed loop will be inductively coupled to the potential wire. The magnetic field of this current will induce a voltage into a nearby signal circuit loop. When *I* is the current through unit length "d*x*" and *H* is the magnetic field intensity at distance r, then the pertinent differential equation is:

$$\frac{\mathrm{d}U}{\mathrm{d}x} = -\mathrm{j}w\mu_0 H \,,$$

where U is induced voltage.

Considering that magnetic flux density $B = \mu_0 H$, and also that according Biot-Savart law:

$$B = \frac{\mu_0 I}{4\pi}\int \frac{\mathrm{d}y}{r} \,.$$

The problem of a finite length conductor oriented horizontally over a conductive plane can be solved by the Neumann Integral. The voltage induced in P due to current I in conductor C is found by Neumann's Integral, which sums the potentials induced in each incremental length "d*y*" of P by each incremental length "d*x*" of C:

$$V_M = \mathrm{j}\frac{w\mu_0 I}{4\pi}\int_0^P\int_0^C \frac{\mathrm{d}x\,\mathrm{d}y}{r} \,. \tag{2}$$

Similarly, the induced potential in P from current I in the image conductor is found by summing all of potentials induced in each incremental length "d*y*" of P originating from current flowing in each incremental length "d*x*" of the image conductor

$$V_D = \mathrm{j}\frac{w\mu_0 I}{4\pi}\int_0^P\int_0^C \frac{\mathrm{d}x\,\mathrm{d}y}{r'} \,. \tag{3}$$

The total mutual impedance, the coupling effect, from the main and image conductors to conductor P is found by combining (2) and (3). The coupling effect is shown in resistance figures, taking into consideration opposite directions of currents flowing in the main and image conductors:

$$Z_{ce} = \frac{V_M - V_D}{I} = \mathrm{j}\frac{w\mu_0}{4\pi}\left(\int_0^P\int_0^C \frac{\mathrm{d}x\,\mathrm{d}y}{\sqrt{(x-y)^2+Y^2}} - \int_0^P\int_0^C \frac{\mathrm{d}x\,\mathrm{d}y}{\sqrt{(x-y)^2+Y^2+h^2}}\right). \tag{4}$$

3 Mutual Coupling Calculation for Practical Configurations

In different papers, hundreds kilometers of the wire lengths, tens of meters of the distances between wires, various frequencies and soil resistivity up to 100,000 Ωm are considered [3, 6 – 8]. In field conditions, the wires lie on the ground surface. In practice, the soil resistivity does not exceed 10,000 Ωm. For practical reasons it is convenient to place them at a distance of 1 m from each other. It should be taken into account that in real conditions testing personnel never uncoil the measuring wires to more than 3,000 m. Considering the fact that the point which refers to measuring resistance lies in the range of 0.5–0.7 of the total current wire length, the distance from the potential electrode to the substation will not be more than 2,000 m.

More than 50 short circuit current recordings in the substations were surveyed. It has been found that the dominant component of substation short circuit current is of power frequency 50 Hz.

The coupling effect (4) development requires solving double integrals of complex expressions. All the calculations were performed by numeric methods with the aid of a personal computer, without an analytic integral's solution, simplifying the task and excluding small components.

From the preliminary calculations it has been seen that for the same soil resistivity, the curves of the coupling effect versus potential wire lengths are practically identical [10]. Based on these results, a family of coupling effect curves was calculated to be determined for different soil resistivities, for any current wire lengths up to 3,000 m and potential wires up to 2,000 m (Fig. 2).

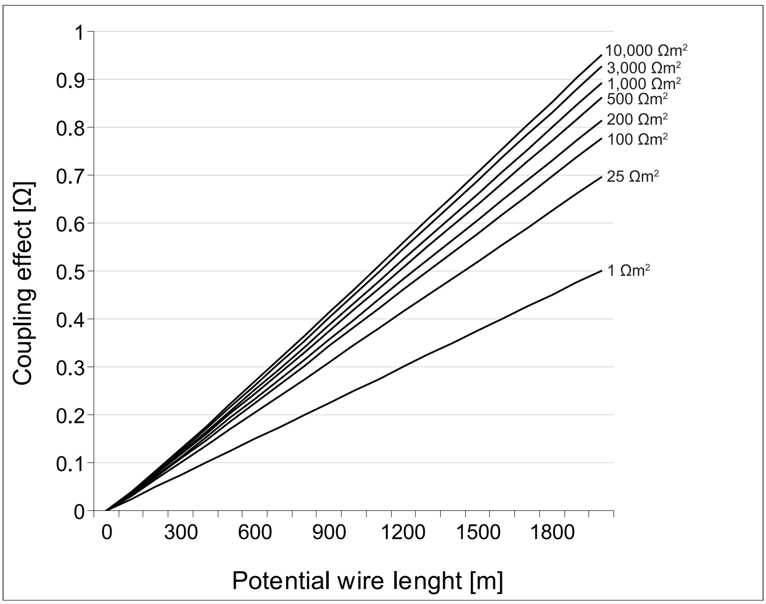

Fig. 2 – *Curves Coupling effect* (*as resistance implement*) *versus potential wire length for* 3 000 m *current wire and different soil resistivities*.

The curves show clearly that the coupling effect grows smaller with decreased soil resistivity. Although for low resistivity soils, station grounding resistance is low also, the coupling effect influence may be still significant. Thus, for every given soil resistivity value, the tester can use only one curve, no matter what the potential wire length is.

It should be clear that although the absolute value of the coupling effect is known, it is insufficient for substation grounding calculation. Substation grounding resistance, as is the value of the coupling effect, is a complex number. The active (resistive) part comprises basically of the resistance between a grounding system and the earth. This component depends of conductor's quantity, system configuration and soil resistivity.

The ground wires of the power lines connect the substation ground system with the ground system of all the towers. The substation ground grid drains part of the fault current only, while the ground wires of the power lines drain another part of the fault current. The main contributor of the reactive component (reactance) is outgoing power lines ground wire inductivity. Fig. 3 puts together the circuit elements discussed above.

The complex nature of the parameters – both substation grounding resistance Z_s and coupling effect Z_{ce} – requires considering them as vectors with particular phase displacement between them. Thus, simple subtraction of Z_{ce} obtained from measurement result Z_m is not enough. The phase angle between involved vectors should be taken into account to achieve considerable accuracy of calculations. In Fig. 4 the vector diagram for the case discussed is shown.

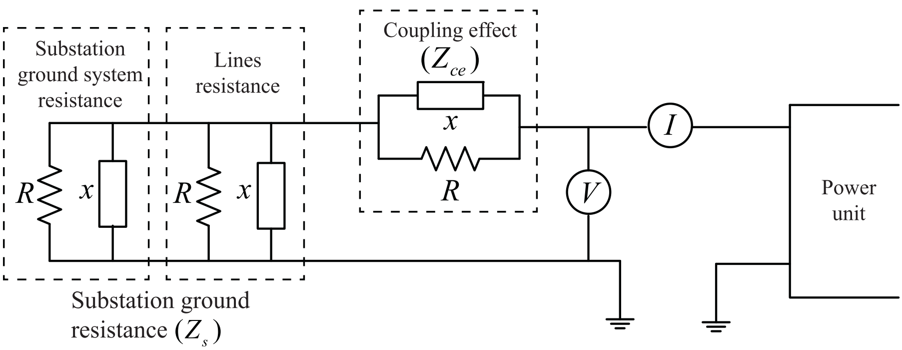

Fig. 3 – *Equivalent scheme of ground resistance measurement circuit.*

In this diagram θ_Z is an angle of the measurement impedance Z_m and θ_{ce} is an angle of the coupling effect. By means of the formula (4), a family of phase angle θ_{ce} curves was developed for different soil resistivities, for current wire lengths 3,000 m and potential wires up to 2,000 m (Fig. 5). It can be seen that the phase angle of the additional complex resistance, due to the coupling effect, does not change significantly with increasing potential wire length up to 2,500 m, for the practical variation of soil resistance (1 ÷ 10,000 Ωm). For almost all wire lengths and soil resistivity ranges, the inductive component of the coupling effect was significantly higher than the active one, thus its' phase angle θ_{ce} was close to 90°. It can be seen that the coupling effect phase angle may be taken for all the cases as approximately $\theta_{ce} = 84°$ with approximation error of as high as 7%.

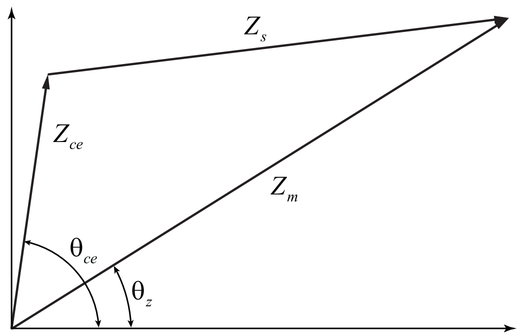

Fig. 4 – *Vector diagram of substation grounding resistance omponents* Z_{ce} *– coupling effect resistance,* Z_m *– measurement result,* Z_s *– substation grounding resistance.*

Measured impedance is the addition of two vectors – actual grounding impedance and the coupling effect. The coupling effect can be easily calculated using the above mentioned method. Thus, actual grounding impedance can be calculated by vector subtraction of the coupling effect from the measurement result

$$Z_s = \sqrt{Z_{ce}^2 + Z_m^2 + 2Z_{ce}Z_m\cos(\theta_{ce} - \theta_z)}\ . \qquad (5)$$

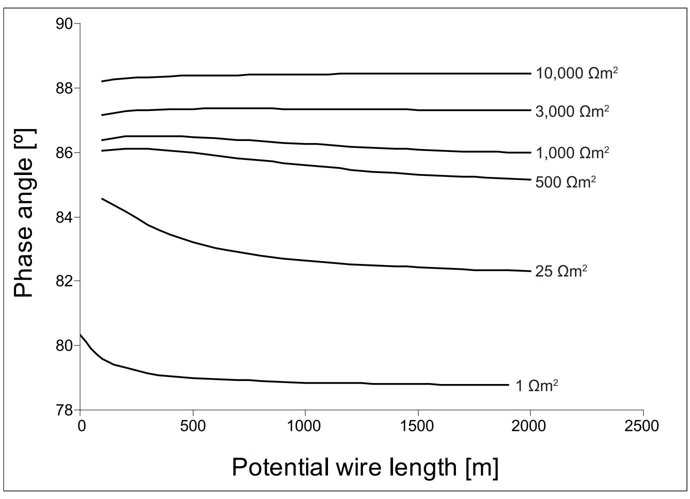

Fig. 5 – *Phase angle in dependence of the potential wire lengths and the soil resistivity for resistance of the coupling effect.*

4 Field Testing

Grounding tests were conducted at four 170/24 kV substations located in rural areas to verify its theoretical design calculations. The sites were checked to ensure there was no underground communication that could influence the measurements. The tests were performed using two methods. In the first method the potential and current electrodes positioned as co-directional and measuring wires were laid in parallel (0°) with a 1 m gap between them. In the second method the measuring wires were positioned at 90°.

All measurements were performed with the substation grounding system in its normal operative configuration which kept all external connections in place. In every case the current and the voltage electrodes were established, making sure the electrode wires were long enough to reach the remote earth. The measurement system enabled directly measuring the complex value of ground resistance impedance with the phase angles.

The value of the coupling effect can be easily found with the help of the curves in Fig. 2 by using the value of the soil resistivity of the area, where the grounding system is installed and the lengths of the potential wire is known. The substation grounding resistance was determined by subtracting the coupling effect value from the measured ground resistance, according to (4). Summary of the measurement results for 4 substations are presented in **Table 1**.

Table 1

Summary of substation grounding resistance measurement results.

No.	Current wire [m]	ρ [Ωm]	Measured value [Ω]	Coupling Effect [Ω]	Final result 0° [Ω]	Final result 90° [Ω]	Results difference [%]
1	350	500	0.224∠45°	0.095	0.164	0.162	1.2%
2	450	50	0.175∠30°	0.084	0.143	0.151	–5.3%
3	600	110	0.161∠59°	0.242	0.118	0.110	6.8%
4	400	230	0.255∠30°	0.162	0.207	0.215	–3.9%

As seen, the difference in the results between the two methods does not exceed 7%. The results obtained confirm the proposed technique to measure the substation ground resistance.

5 The Developed Method for Group Resistance Estimation

Thus, the measuring and calculation of substation ground resistance can be performed as follows:

1) Substation ground resistance Z_m and angle between active and reactive components of the measurement result θ_Z is measured by the fall of the

potential method. During measuring, the potential electrode is situated on the line between the substation and the current electrode. Current and potential wires are placed at a distance of 1 m from each other.

2) Average soil resistivity in the area of the substation ground resistance is measured by any method (for example, the Wenner method [11]). The coupling effect value Z_{ce} is defined by curves in Fig. 2, according to wire lengths and soil resistivity. For substation ground resistance calculations, the coupling effect phase angle $\theta_{ce} = 84°$ could be used or could be selected more accurately by curves in Fig. 5.

3) Required substation ground resistance Z_s is calculated by (5).

6 Conclusion

A method for substation grounding resistance measurement, taking into account the coupling effect, has been developed. The real substation ground resistance can be found by subtracting from measured ground resistance results an estimated correction factor. This factor takes into account the error caused by the coupling effect.

Practical comparative measurements were performed to prove the proposed method. Comparison was carried out with a method of measurements, where the testers situated the electrode wires with 90° between them. The coupling effect is absent in this method. The proposed method allows correcting the substation measured resistance, so that it is possible to subtract the coupling effect from this resistance without using difficult calculations.

7 Acknowledgment

Alex Farber, senior group engineer is now a Ph.D. candidate in Electrical Engineering of Tel Aviv University. The authors express his appreciation to Prof A. Braunshtein from Tel Aviv University, who directed his work and served as major advisor.

8 References

[1] G.F. Tagg: Measurement of Earth-electrode Resistance with Particular Reference to Earth-electrode Systems Covering a Large Area, Proceedings of the Institution of Electrical Engineers, Vol. 111, No. 12, Dec. 1964, pp. 2118 – 2130.

[2] IEEE Standard 80-2000 – IEEE Guide for Safety in AC Substation Grounding, NY, USA, Aug. 2000.

[3] E.J. Rogers, J.F. White: Mutual Coupling between Finite Lengths of Parallel or Angled Horizontal Earth Return Conductors, IEEE Transactions on Power Delivery, Vol. 4, No. 1, Jan. 1989, pp. 103 – 113.

[4] J.R. Carson: Wave Propagation in Overhead Wires with Ground Return, Bell System Technical Journal, Vol. 5, No. 4, Oct. 1926, pp. 539 – 554.

[5] R.M. Foster: Mutual Impedance of Grounded Wires Lying on the Surface of the Earth, Bell System Technical Journal, Vol. 10, No. 3, July 1931, pp. 408 – 419.

[6] IEEE Standard 81.2-1991 – IEEE Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems, NY, USA, Jan. 1991.

[7] H.G. Sarmiento, P.H. Reynolds D. Mukhedkar: An Extension to the Study of Earth-return Mutual Coupling Effect in Ground Impedance Field Measurements, IEEE Transactions on Power Delivery, Vol. 3, No. 1, Jan. 1988, pp. 96 – 101.

[8] J. Ma, F.P. Dawalibi: Influence of Inductive Coupling between Leads on Ground Impedance Measurements using the Fall-of-potential Method, IEEE Transactions on Power Delivery, Vol. 16, No. 4, Oct. 2001, pp. 739 – 743.

[9] A. Deri, G. Tevan, A. Semlyen, A. Castanheira: The Complex Ground Return Plane Simplified Model for Homogeneous and Multi-layer Earth Return, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No. 8, Aug. 1981, pp. 3686 – 3693.

[10] A. Farber, B. Katz: Israel Electric Validates Earthing Measurements, Transmission and Distribution World, Vol. 61, No. 7, July 2009, pp. 52-56.

[11] J.G. Biddle: Manual on Ground Resistance Testing, Philadelphia Electrical and Scientific, Philadelphia, PA, USA, 1970.