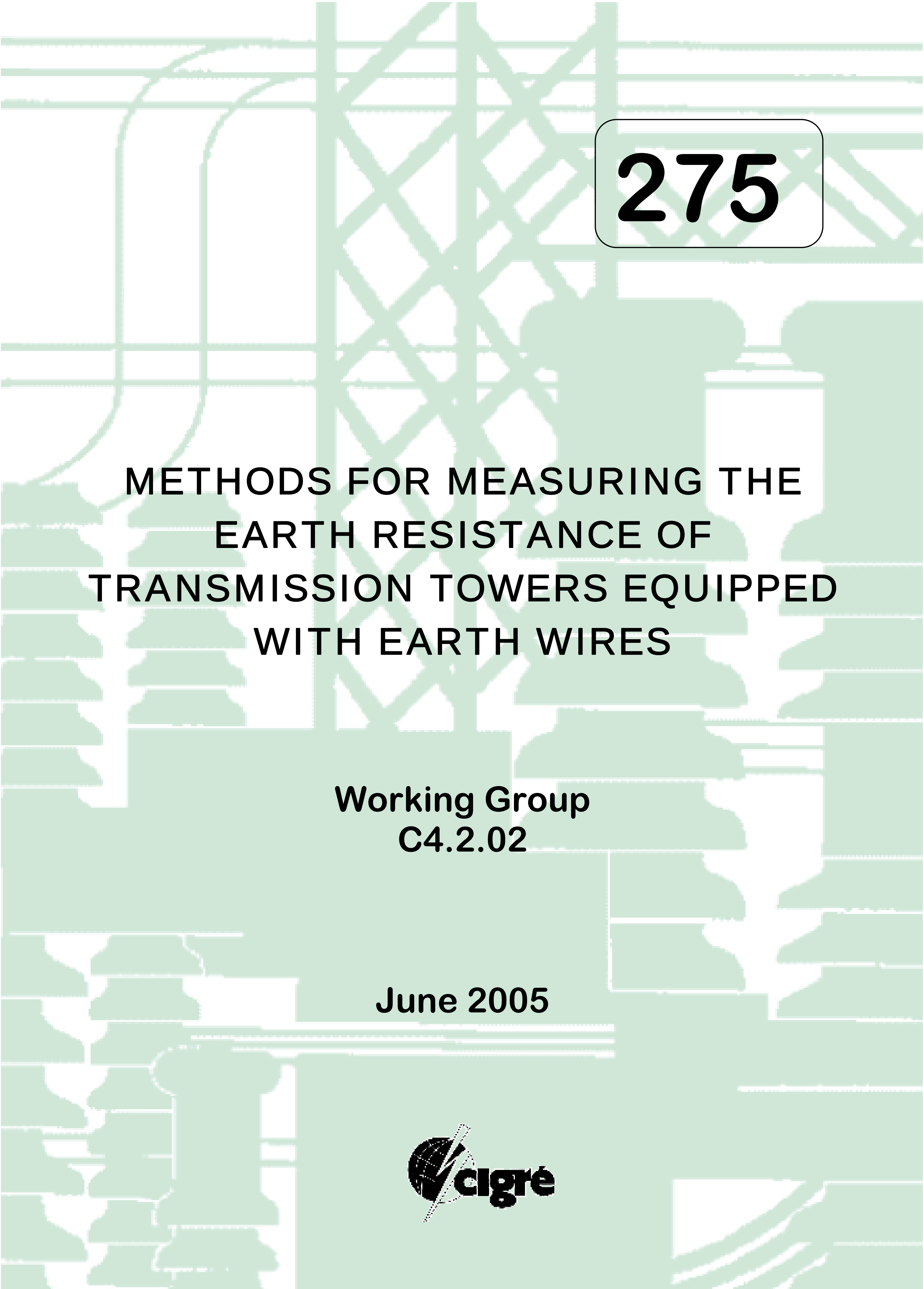

275

METHODS FOR MEASURING THE EARTH RESISTANCE OF TRANSMISSION TOWERS EQUIPPED WITH EARTH WIRES

Working Group
C4.2.02

June 2005

cigré

METHODS FOR MEASURING THE EARTH RESISTANCE OF TRANSMISSION TOWERS EQUIPPED WITH EARTH WIRES

Working Group
C4.2.02
(Former WG 36.02)

Members of the Former Working Group 36.02:

L.-E. Juhlin (Sweden) Convener

D. Halkin (Belgium), G. Lucca (Italy), H.-G. Öhlin (Sweden), L. Pandini (Italy), O. Wattier (France)

Former members during work with the document: GL. Solbiati (Italy) (Former Convener),
C. Dörnemann (Germany), B. Nguyen (France), C. Palú (Italy). H. Rochereau (France)

Corresponding members: A.C. Britten (South Africa), D. O. Campones do Brasil (Brazil), J. Diesendorf (Australia), H.E. Nerhood (USA), M. Tibensky (Canada), J.M. Thorson (USA), J. Wilk (Poland)

TABLE OF CONTENTS

ABSTRACT

The study presented in this report is based on a survey of CIGRE members of the Working Group 36.02 of former Study Committee 36 (now WG C4.2.02). Its goal is to make an inventory of methods for measuring the earthing of transmission towers, which are equipped with earth wires, and to compare the methods.

1. MEASUREMENT OF TOWER EARTHING

1.1. Introduction

The earthing of overhead transmission lines has an important influence on:

- Reducing the number of faults in power systems.
- Dealing with effects of proximity between power systems and railway or telecommunication systems.
- Ensuring the safety of people near towers.

Knowing the earth resistance with sufficient accuracy (see section 1.3) is essential for utilities in relation to their internal and external constraints. However, according to the earth electrode's own characteristic, it is essential to know exactly what is important to be measured.

1.2. Frequency Dependence of Tower Earth Impedance

We are therefore interested in earthing behaviour at 50 Hz (for safety and proximity problems) and under lightning surge (in order to evaluate back flashover numbers), and therefore we are interested in frequencies from 50 Hz to about 1 MHz. The earthing can be simply described as a resistance (soil resistance) in series with an inductance (the wire forming the earth connection).

For low frequencies the earth impedance is a pure resistance and remains constant and equal to its d.c. resistance. At high frequency, the earthing behaviour is inductive (the impedance value increases with the square root of the frequency). The cut-off frequency is between 100 kHz to 1 MHz; it decreases with the electrode length and increases with the soil resistivity.

Within these parameters, one tries to design the earthing system so that it maintains a resistive component (the cut off frequency must be compatible with the lightning spectrum). We will consider that the earth impedance is flat between 0 and 1 MHz.

1.3. Measurement Accuracy

The measurement accuracy required will take into account the two following points:

- The value of earth resistance can vary greatly depending on the climatic conditions prevailing at the time of measurement. In practice, values for deep earth electrodes show variations of about 20%.
- For high currents (hundreds of amps, depending on soil characteristics) earth resistance values decrease. This behaviour is due to flashover in the soil that reduces the apparent resistivity of the soil. The measured earth resistance can be overestimated since the measuring current is less than one hundred amperes.

It therefore seems of little interest to use an apparatus or method giving an accuracy better than 20%.

2. THE PROBLEM

It is quite easy to measure tower earth resistance when the line is not equipped with an earth wire. This is more difficult when the towers are connected together by means of an earth wire.

The measurement of a “simple” earth electrode is done by the fall in potential method. The objective is to inject current into the earth electrode and to measure the electrode potential referenced to a remote earth and the current I (see Section 4). R is then given by the ratio V / I.

When the towers are connected together by means of an earth wire, all of the earth resistances of the towers are in parallel; so the measurement made at one tower gives a global value of the earth resistances of all the towers, seen from the point of measurement, and not the earth resistance of that particular tower.

Various solutions have therefore been implemented in different countries to overcome this obstacle.

3. ANALYSIS OF RESPONSES

In about 1995 Working Group WG02 of Study Committee 36 carried out a survey of methods used for measuring the earth resistance of towers equipped with earth wires. Eleven countries replied, as follows:

- Seven use an high frequency measuring method (ABB HW2A equipment): France, Germany, Belgium, Spain, Great Britain, Italy and South Africa;
- One uses the repeated voltage impulse method (Poland);
- Three use the method, which needs the disconnection of the overhead earth wires (United States, Finland and the Czech Republic) and the earth resistance is then measured with the help of a classical earth tester. This solution is complex as either the test team works with the system live or the line must be put out of service.

Other methods are also described in this report; some of them are in use on power systems (the determination of the earth resistance using the fall of potential curve is used in France), some of them are only experimental.

4. SUMMARY OF EARTH IMPEDANCE MEASUREMENT FOR TOWERS NOT EQUIPPED WITH AN EARTH WIRE

The measuring equipment uses the principle of the fall in potential method [1], [2], [3] and [4], described below.

A current I is injected between the electrodes X (the one under measurement) and C (the auxiliary current electrode) and the potential difference V is measured between the electrodes X and P (the auxiliary potential electrode), see Figure 1. The ratio V/I under certain conditions gives the resistance R of the electrode X.

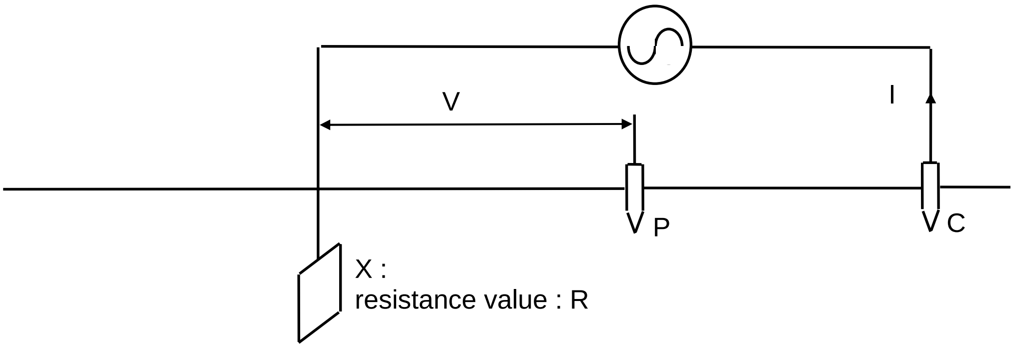

Figure 1: Apparatus layout

The three electrodes X, P and C are in line and P is placed between X and C at a distance from X which is about 62% of the distance XC. This rule, established by Tagg [1] (Appendix A), considers the earth as a homogeneous medium.

The earth potential difference V between electrodes X and P, according to the position of P, is given in Figure 2 (dotted curve) (see Appendix A). It is equal to R·I when PX is about 62% of XC.

The earth potential (relevant to remote earth) rise shape is also shown in Figure 2 (thick curve).

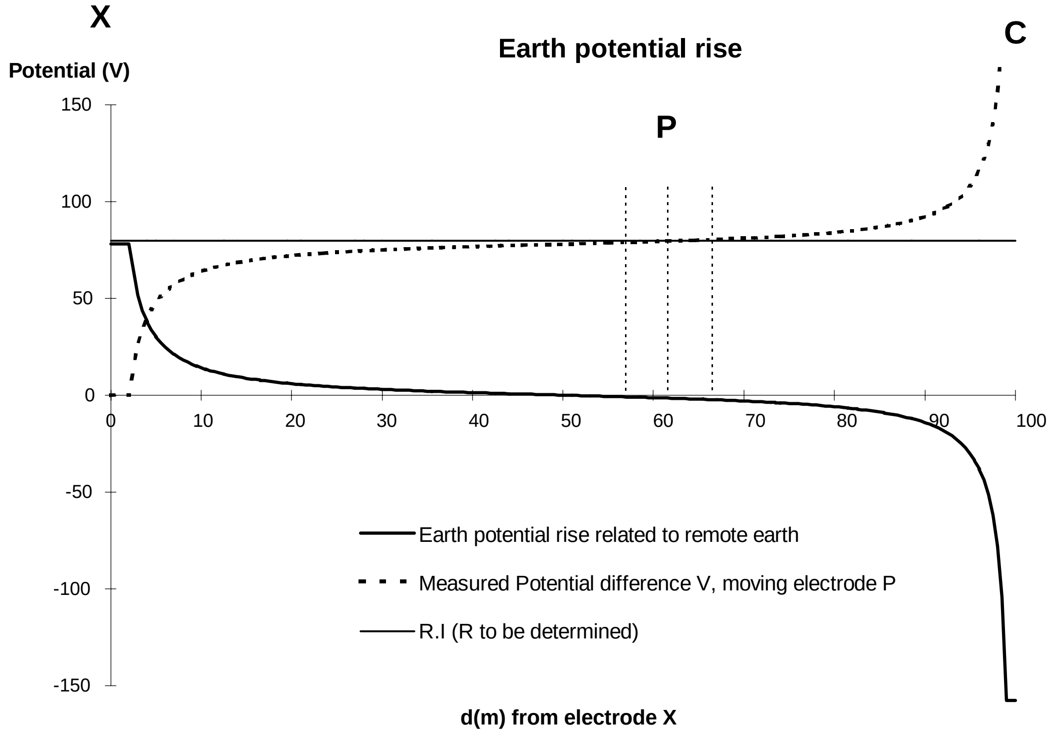

Figure 2: Earth potential rise in the soil versus the distance

If the two electrodes X and C are far enough apart, so that their interaction is negligible, the difference of potential between P and X is equal to R·I and the earth potential at P is equal to 0 ("remote earth"), then the measurement can be considered to be good and application of the Tagg rule is not necessary.

It can be seen from the curves of Figure 2 that for large distances between the electrodes, the measurement is good enough even for a large range of position of P.

When the earth is very heterogeneous, the position of P can change considerably when compared with the case with a homogeneous earth. In practice, one should check that the interaction between X and C is not too strong, by moving the electrode P along the line XC to check the constancy of the measured resistance. If it is not then electrode C is put further away.

In practice, for a good measurement, a distance 75 m for CX and 40 m for PX is enough for a tower earthing grid whose equivalent radius (see Section 6.4) is less than 5 m, which it usually is.

The classical earth tester, used when the tower is not equipped with earth wires, uses this fall in potential method, by applying a power source which delivers a current I between the earth electrode X to be measured and the auxiliary injection current probe C, and using a device measuring the quotient V/I, therefore, directly displaying the earth resistance value R.

5. MEASUREMENT ON TOWERS EQUIPPED WITH EARTH WIRES

5.1. Equivalent Circuit of Earthing Network

Where the power lines have earth wires, the earths of each tower are connected together by the earth wire. Therefore, the earthing system is the one shown in Figure 3.

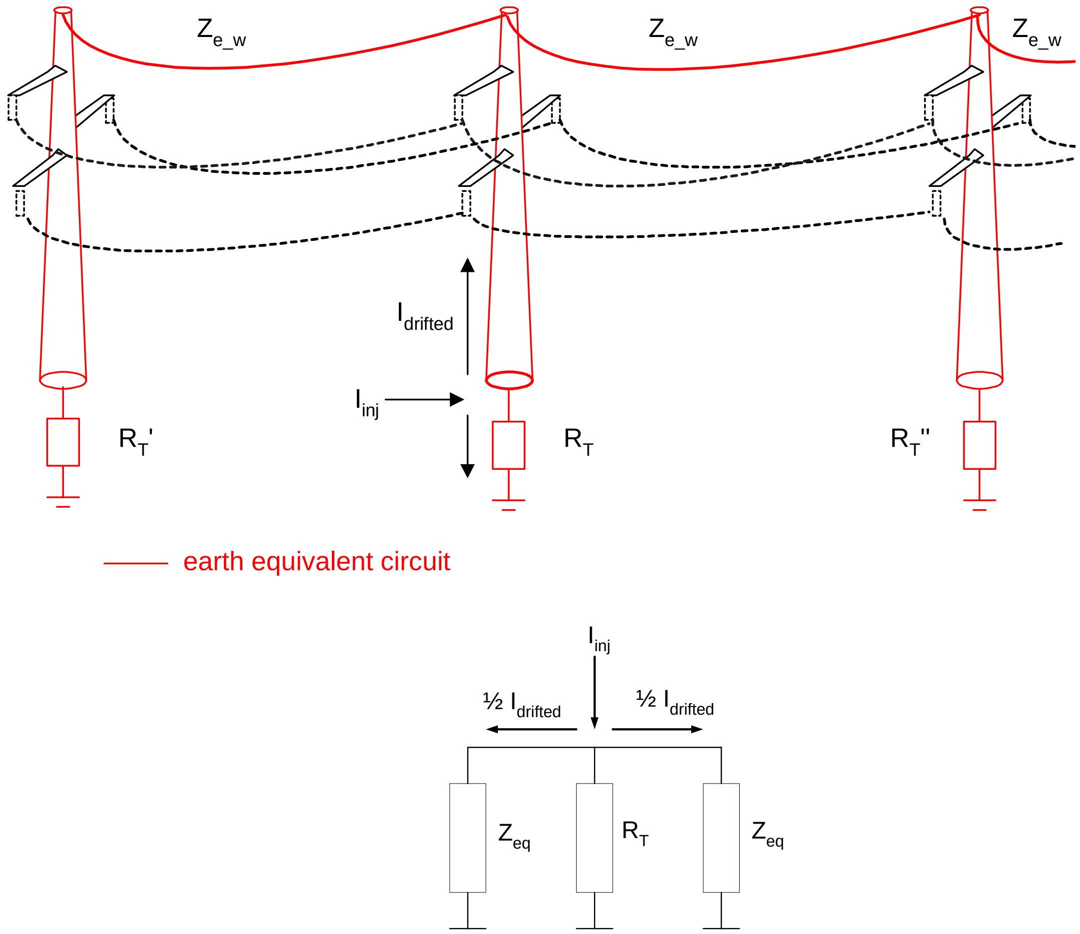

Figure 3: Equivalent circuit of an earth wire with earth return

When applying the earth impedance measuring method described at Section 4 we must consider that a significant part of the current I is injected into the soil not through the earthing of the tower under measurement, but deviated through the earthing of adjacent towers via the earth wire. Consequently what is measured is not the earth impedance of the tower R_T but the impedance of the earth network

R_T // R_T‘ // R_T’’ // ... = R_T // Z_{eq} // Z_{eq} = R_T // (Z_{eq} / 2).

It is useful to remember that Z_{eq} is frequency dependent.

To measure the tower earth resistance, two solutions are available:

- Measure directly the current flowing through the earth electrode of the tower being measured.
- Reduce the current deviated into the earth wire to a value which can be neglected.

In these two cases, the injected measuring current will be strong enough for the interfering currents to be neglected.

5.2. Interference Currents

The earth wire circuit with earth return carries current at 50 Hz (and harmonics) induced by the currents in the live conductors. Others currents at different frequencies can also perturb the measurement. For this reason potentials of several tens of volts can be measured on earths connected to earth wires. The measuring instrument, of whatever sort, must therefore efficiently filter these interfering currents. It is also necessary, because of this interference at different frequencies, to have a strong injected measurement current in order to have a good signal to noise ratio.

6. DESCRIPTION OF THE DIFFERENT METHODS USED

6.1. High Frequency Measurement Method

6.1.1. The Principle

The main idea is to adapt the potential fall method by using a high frequency for the injected current in such a way that the value of Z_{eq} becomes much higher than R_T so that the current diverted to other towers becomes very small. For frequencies lower than about a hundred Hz, the impedance Z_{eq} is much too low for the diverted current to be neglected.

6.1.2. High Frequency Apparatus and Wiring

At high frequencies, the capacitive and inductive coupling between the current injection circuit and the voltage measuring set (at the inputs of the apparatus and on the leads) can dominate and distort the value of the measured resistance if precautions are not taken:

- Conductors must be located so as to reduce mutual coupling between voltage and current leads; a minimum distance between the two circuits has to be maintained.
- Auxiliary earth electrode resistances must be limited (typically to some hundreds of ohms) in order to reduce capacitive coupling.

At high frequency, when the wavelength is of the same order as the length of the measuring cables, there may be a risk of resonance phenomena involving standing waves in the measuring cables linking the measuring probes to the earth tester, which can be 45 to 75 m long. However studies and measurements of the high frequency behaviour of earth electrodes have shown that the measurement method can be used for frequencies up to 1 MHz without introducing circuits to modify the impedance.

6.1.3. *Equivalent Circuit*

The earth electrode - earth wire circuit will be modelled with the help of transmission line theory [5]. The circuit is presented below:

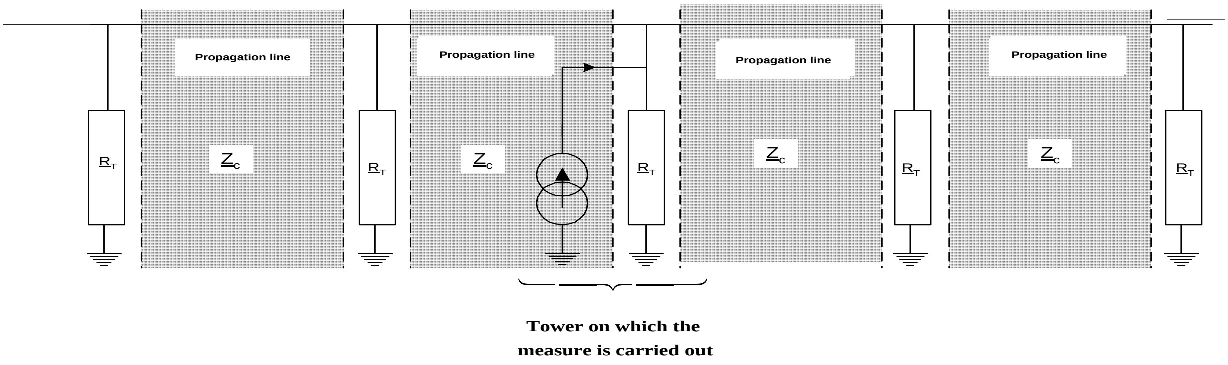

Figure 4: Equivalent circuit of an earth wire with earth return

R_T (Ω): resistance of the tower earth electrode
$\underline{Z}c$ (Ω): characteristic impedance of the circuit earth wire with earth return

$$\underline{Z}_c = \sqrt{\frac{r + jl\omega}{jc\omega}} \qquad (1)$$

r (Ω/m): resistance per unit length of the circuit earth wire with earth return
l (H/m): self-inductance per unit length of the circuit earth wire with earth return
c (F/m): capacitance per unit length of the circuit earth wire with earth return

These values are related to earth at the frequency of measurement.

Considering the lumped parameters (for towers far away from the substation, the hypothesis are that the span lengths L_p and the tower earth resistances R_T are identical), $\underline{Z}_{eq}$ is given by [3]:

$$Z_{eq} = \frac{1}{2}\left(Z_{earthwire} + \sqrt{Z^2_{earthwire} + 4Z_{earthwire}R_T}\right) \qquad (2)$$

where

$$Z_{earthwire} = (r + jl\omega)\cdot L_P \qquad (3)$$

Using the line theory, the impedance relevant to a span length and referred to the origin of the line, is given by:

$$\underline{Z}_r(0) = \underline{Z}_c \times \frac{R_T + \underline{Z}_c \tanh(\underline{\gamma} L_p)}{\underline{Z}_c + R_T \tanh(\underline{\gamma} L_p)} \qquad (4)$$

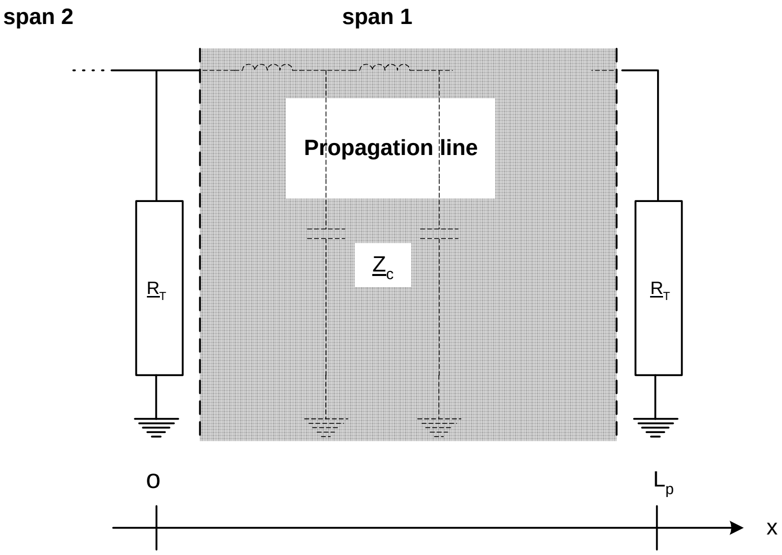

Figure 5: Equivalent circuit of a span of the circuit earth wire with earth return

L_p (m):	length of span
$\underline{Z}_r$ (0):	impedance referred to the origin of the span
γ:	propagation constant

$$\underline{\gamma} = \sqrt{(r + jl\omega) \times jc\omega} \tag{5}$$

r can be neglected for usual values of the earth wire resistance.

It is then possible to build up an equivalent circuit according to the principle shown in Figure 5 for the first span. The operation is reiterated on the next span starting with equivalent impedance R_T // $\underline{Z}_r$ (0), and so on.

For a given tower, depending on the number of spans on the right and on the left sides of it, the equivalent circuit can be determined as in Figure 6, where $\underline{Z}_{AG}$ is the equivalent impedance of the line towards the left and $\underline{Z}_{AD}$ is the equivalent impedance towards the right.

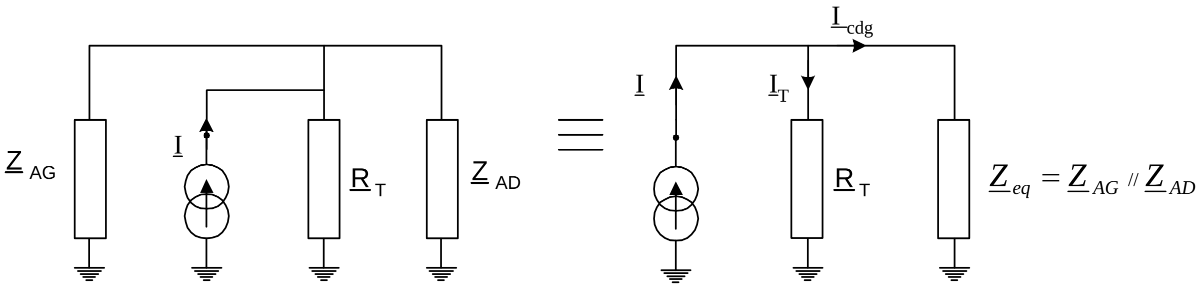

Figure 6: Equivalent circuit of the earth wire with earth return circuit, seen from a given tower

6.1.4. Application to the Measurement of Tower Earth Resistance

The objective is to calculate the frequency value f for which Z_{eq} is much higher than the tower earth resistance R_T to be measured.

The value of $\underline{Z}_{eq}$ versus the frequency f is plotted in Figure 7. They are compared with the values of the impedance calculated with lumped element theory (dotted curve). For example, for a 400 kV line with a single earth wire, (the hypothesis described in Section 4.3.4), the two curves are similar up to about 30 kHz.

We confirmed that for frequency above about 30 kHz, it is better to study the circuit of an earth wire with earth return by using the propagation line theory instead of considering lumped parameters.

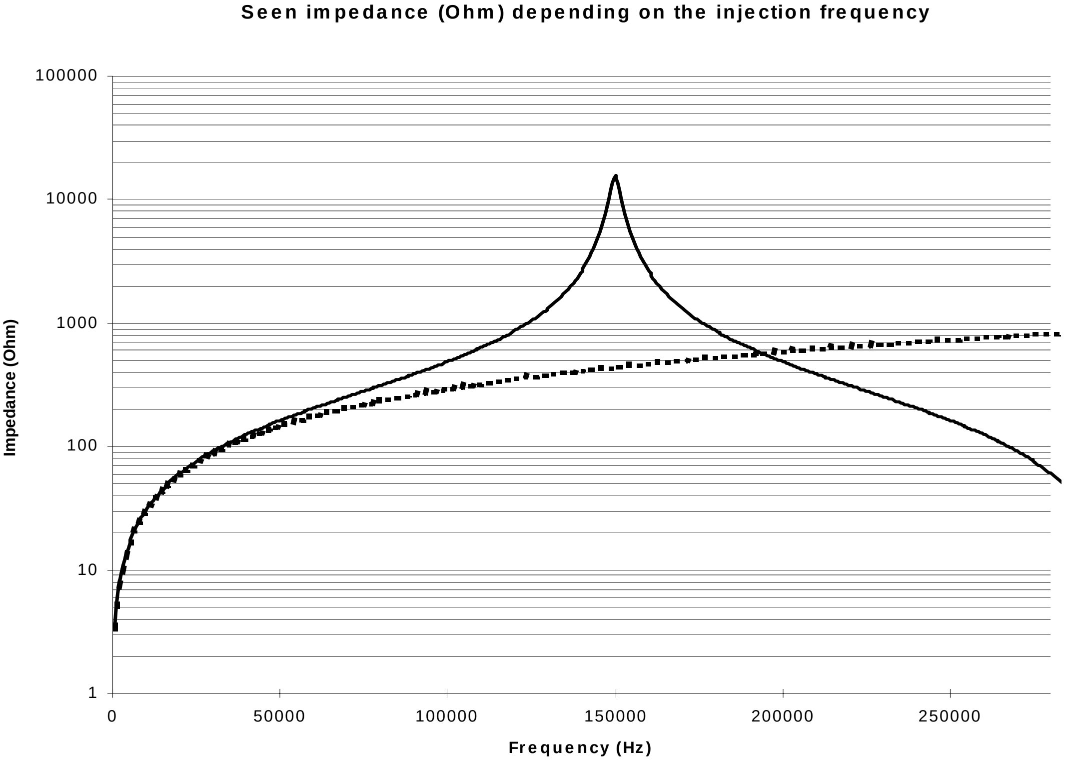

Figure 7: Equivalent impedance as a function of frequency

The maximum for $\underline{Z}_{eq}$ (see Section 4) according to transmission line theory is reached at:

$$f = \frac{2n+1}{4} \times \frac{1}{L_P \sqrt{l \cdot c}} \tag{7}$$

Depending on the length of span (from 1000 m to 200 m) the maximum is reached for one frequency in the range 50 - 400 kHz.

At these frequencies (above 100 kHz), it is necessary to check that the earthing can still be considered as a pure resistance and therefore equal to the earth impedance at 50 Hz, taking account of the layout of the earth electrodes of the tower and of the resistivity of the soil.

6.1.5. Numerical application at the optimal frequency

The error made by the measuring method ε at different frequencies can be deduced in relation with the resistance value of the tower earth electrode. The study was conducted in two cases, far away from the substation and at the exit of the substation, on a 400 kV line equipped with a single earth wire.

For a line equipped with two earth wires the error is more important.

The input data are as follows:

- Earth resistances of the towers: all are equal
- Earth resistance of the substation: 0.2 Ω
- Span length, L_p: 500 m (all the span lengths are equal)
- Earth wire height: 46.5 m
- Earth wire section: 147mm²
- Earth wire material: steel - aluminium
- Earth wire resistance per unit length, r: 0.467 Ω/km
- Inductance per unit length of the circuit earth wire with earth return, l: 1.9×10^{-6} H/m
- Capacitance per unit length of the circuit earth wire with earth return, c: 5.9×10^{-12} F/m

In this case, the optimal frequency for $\underline{Z}_r(0)$ and thus for $\underline{Z}_{eq}$ is 150 kHz.

6.1.5.1. Far away from the substation

400 kV	f = 150 kHz					
Rt (Ω)	1	5	10	20	30	50
ε (%)	0	≈ 0	≈ 0	0,25	0,5	1,5

It can be seen that the under-estimation of the earth resistance of the tower remains small even with high earth resistance values.

An example for 26 kHz is given below for the same assumptions:

400 kV	f = 26 kHz					
Rt (Ω)	1	5	10	20	30	50
ε (%)	≈ 0	0.5	2	5	10	20

In this case the under-estimation on the earth resistance of the tower is greater, and becomes significant when the earth resistance value exceeds 50 Ω.

6.1.5.2. Tower at the exit of the substation

At this tower location, a more significant proportion of the injected current diverts to the substation earth (which usually has a very small resistance value) via the earth wire. Moreover, the first span from the substation is generally short: the equivalent impedance is then much lower than for a standard span.

For the calculation, the impedance used is that of the first 150 m from the substation.

400 kV	f = 150 kHz					
Rt (Ω)	1	5	10	20	30	50
ε (%)	0	0	0	0.5	1	2

At 150 kHz, the error remains very small.

An example for 26 kHz is also given below with the same assumptions.

400 kV	f = 26 kHz					
Rt (Ω)	1	5	10	20	30	50
ε (%)	0	1	5	10	20	35

It is clear that measurements at this frequency for a tower close to a substation must be used with care.

We can see from the previous example that a good measurement solution is an apparatus with a range of frequencies in order to determine the more appropriate frequency to be applied to different line configurations (span length and earth resistance of towers).

The choice of the frequency will essentially be a compromise between the measurement accuracy and the possibility and the cost of processing the coupling connection interference appearing in the equipment and in the leads. The French experience showed that above several tens of kHz, in spite of taking precautions over cable layout, coupling becomes dominant.

A method based on this principle, using a range of frequencies is envisaged in South Africa and France. It operates by sweeping a spectrum of frequencies so as to find where the resistance of the rest of the line is highest and therefore discards the diverted current best. The method does not seem to have been implemented in South Africa. In France a prototype has been developed [6].

An instrument [7] using this measuring method with injection of a constant frequency current (26 kHz) is available commercially.

6.2. Earth Resistance Measurement Using Voltage Impulses

This method was put forward by Galeazzi et al of Padua University in Italy in 1954 [8]. It is based on the reflection of a voltage impulse applied to the earth electrode of the tower and allows the electrode's behaviour under lightning stroke to be determined.

A fast fronted voltage waveform, of order 1 μs rise time and 1000 V peak amplitude (frequency range 0 to 1 MHz), is applied between the tower and the earth, thus spreading current to the other towers via the overhead earth wire (characteristic impedance Zc ≈ 500 Ω) and in the earth.

The tower earth resistance R_T (< 25 Ω) can be considered to be localised and the impedance of the tower is negligible. The impedance seen by the impulse wave generator is therefore three impedances in parallel: R_T and Zc twice. This applies for times less than the time taken for first reflection wave to return from the adjacent towers.

The electrical circuit is described in Figure 8:

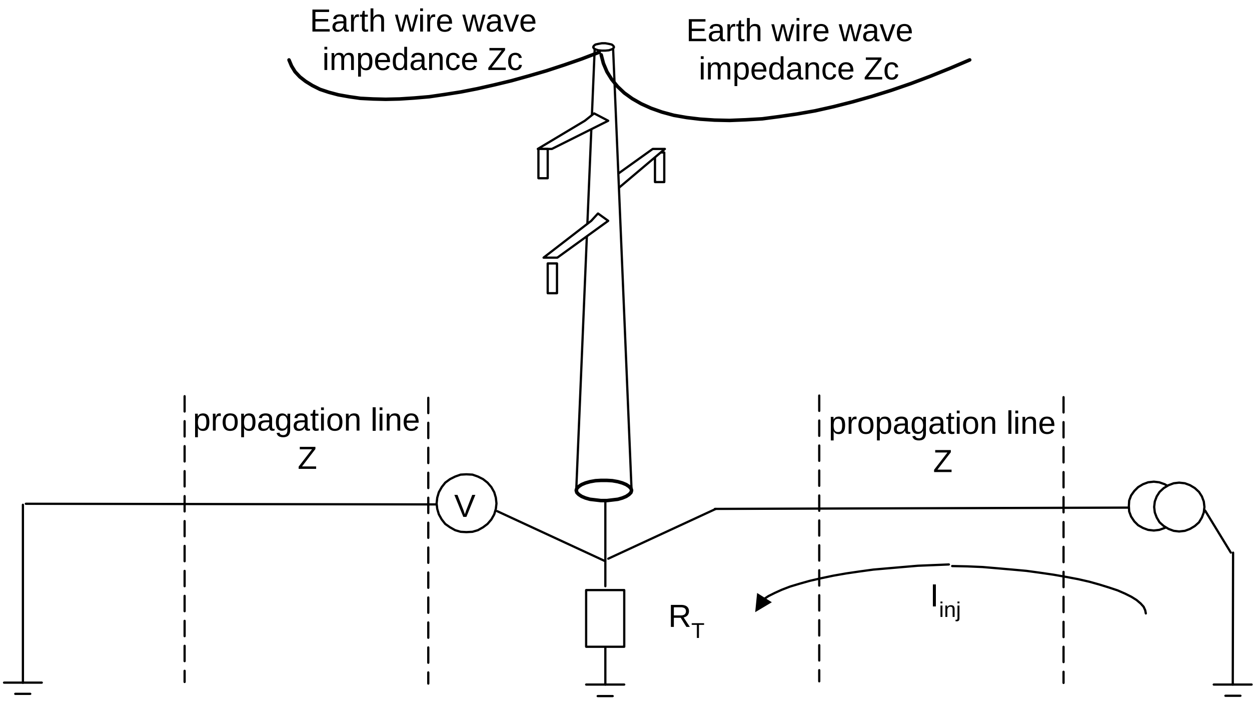

Figure 8: Equivalent circuit for the voltage impulse method

In practice, the impulse wave generator produces about a hundred impulses per second and these are applied alternately to the tower earth and to a standard resistance inside the instrument R_x, having a variable value between 0 and 100 Ω. The two voltages are then compared to each other on an oscilloscope.

The tower resistance R_T (on a tower remote from a substation) is deduced from the following formula:

$$R_x = R_T \frac{1}{1 + 2\frac{R_T}{Z_c}} \qquad (8)$$

The method is used in Poland [9]. The voltage waveform is 1000 V peak and 0.5 μs rise time. The standard resistance can have the following values: 2, 5, 10, 20, 50 and 100 Ω. However, no indication has been given about the accuracy of the method. Similar equipment was tested more than 20 years ago in Belgium and abandoned due to a lack of satisfactory results.

In France, this method is used successfully to obtain the response of the earth electrode to a lightning stroke current. But, of course, this electrode is not connected to a shield wire. Anyway, the apparatus display is too complex to be used in an operational way. The current circuit and the voltage circuit cables do not need to be adapted on their wave impedance in order to avoid reflections at their ends (see 6.1.2) but are installed at right angles to avoid all inductive interactions.

6.3. Use of a Classical Earth Tester with a Ring Current Transformer to Measure the Injected Current

The use of a classical earth tester to measure the earth resistance of a tower does not give accurate results because part of the injected current is diverted through the overhead earth wires to towers other than the one being measured. One possible solution therefore consists of measuring the real current injected in the tower earth electrode using the fall of potential method. This can be done with the help of a ring current transformer placed around the earth's electrode down lead (Figure 9).

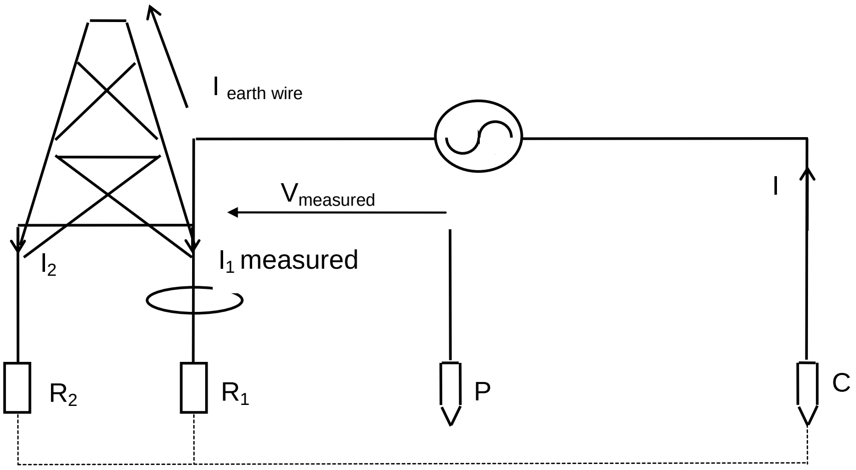

Figure 9: Apparatus Layout

As explained in Section 5.2, it is necessary to be able to discriminate the injected current from the interfering currents that are flowing continuously to earth.

The system [10] is essentially for application to distribution installations because the diameter of ring current transformers prevents them from being used on power systems towers.

Note 1: The mutual impedance that would divert current towards the others towers can be neglected for frequency lower than 100 kHz.

Note 2: Safety precautions have to allow for a short circuit.

Note 3: The current transient in the footing must be measurable. So either the low frequency current source must be powerful enough or a high frequency injection will be required.

For power systems, Rogowski coils could be more suitable.

6.4. Determination of the Earth Resistance by Calculation

It is possible to evaluate the earth resistance of the tower electrode by using the following formula (given by [3]):

$$R = \frac{\rho}{2\pi r_e} \qquad (9)$$

where ρ is the equivalent soil resistivity and r_e is the equivalent radius of the earth electrode (the radius of a hemispherical earth impedance, equivalent to the actual earth impedance).

It is quite easy to determine the resistivity of homogenous earth in the vicinity of the tower using the four-terminal method. See for example the Wenner method [1], and [2]. Depending on the soil environment it is advisable to make two perpendicular measurements of the resistivity.

Then, the equivalent radius r_e can be determined from the geometry of the electrode.

For example the equivalent radius r_e of a rod vertically buried in a homogeneous soil is [11]:

$$r_e = L \frac{1}{\ln(\frac{4L}{d})} \qquad (10)$$

where L is the length of the rod and d is its diameter.

If the soil is not homogeneous or/and the earth electrode geometry is more complex, computer simulation is required [3] to reach the same accuracy.

6.5. Method Using Fall of Potential Curve

This method, used in France, makes it possible to validate the measurement of the earth resistance by the high frequency method while being able to carry out a consistency check.

- First the earth electrode value $R_{t\ \mathrm{estimeted}}$ is measured with the high frequency method and also with a classical earth tester (in that case, $R_{t\ \mathrm{estimeted\ LF}}$ is lower than the real value R_t because the diverted current is then important).
- The equivalent radius r_e is estimated by "drawing" the fall of potential curve: earth electrode resistance R(d) is measured for different distances d from the tower of the voltage probe P (see Section 4) according to the fall of potential method at high and also low frequency. Then one must check that (11) is true for all distance d between 1 and 50 m from the tower and whatever the value of deviated current in the earth wire (i.e. whatever the injection frequency). When the measure is made at low frequency, the equivalent radius value is correct but the $R_{t\ \mathrm{estimeted\ LF}}$ value is in error (lower than R_t).

$$R_{t\ estimated} \times r_e = d \times (R_{t\ estimated} - R(d)) \qquad (11)$$

- Soil resistivity ρ is then measured and we can check then that:

$$\frac{\rho}{2\pi} = R_{t\ measured\ HF} \times r_e \qquad (12)$$

7. CONCLUSIONS

Among the various ways of measuring the tower earthing, the disconnection of the earth wire is the most accurate and the only one that allows a precise measurement in every case. On the other hand, the work has to be done with the circuits live or with the line taken out of service. This represents a heavy investment for a superfluous level of precision.

Indeed, the value of the earth electrode resistance can vary significantly over time and with the climatic conditions at the time of measurement. Therefore, in the majority of cases an estimate of the value is more than sufficient for the operation of the electricity system.

Accordingly, the variable high frequency method, used with a strict operational method, or the use of a classical earth tester with a ring current transformer to measure the injected current, appear to be the most accurate methods for making measurements on towers with earth wires, especially on towers which have a high value of earth resistance or are very close to a substation. However, for most towers in a line the widely used method based on the injection of a high frequency current gives sufficient accuracy, taking into account the limitations for towers located very close to a substation, see Section 6.1.5.

REFERENCES

[1] G.F. TAGG, Earth resistances. George Newnes Limited, London, (1964)

[2] IEEE, Standard 81-1983, IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System (Part 1)

[3] F. DAWALIBI et Al. Transmission line grounding. Vol. 1, EPRI EL- 2699 Final report Oct 1994

[4] P.G. LAURENT, Guide sur le calcul, l'exécution et la mesure des prises de terre, Revue Générale d'Electricité T 81 N° 7/8 et 9 (1972)

[5] F. GARDIOL, Electromagnétisme Vol III du traité d'électricité, d'électronique et d'électrotechnique Ecole Polytechnique Fédérale de Lausanne (DUNOD)

[6] Tellurohmètre HF EF 1001 by EMC Systems, 39 rue Gainsbourg F - 94200 Ivry s/s Seine France

[7] J. UFERMANN, K. JAHN, High frequency Earth resistance measuring instrument , Brown and Boveri journal N° 3/67

[8] A. GALEAZZI, R. MARENESI, A. PAOLUCCI Université de Padoue, (Italie) Ohmmètre de terre en ondes de chocs pour la détermination des résistances de terre dans les lignes de transmission avec fil de garde Rapport CIGRE N° 329, 1954

[9] Mrs GALEWSKI, WOJTAS, WOLOSZYK Technical University of Gdansk (Poland) Impulse earthing impedance measurements XIV Imeko World congress 1 - 6 june 1997 Tampere, Finland.

[10] Earth tester UNILAP GEO X NGI Norma Goerz Instruments GmbH D-90411 Nürnberg Bennostrasse 6 Germany

[11] CENELEC, Standard for general design requirements of overhead electrical lines exceeding 45 kV (AC) CENELEC TC11

Appendix A

Calculation of the potential electrode's optimal position

Tagg [1] was the first to establish the "61.8% rule" which is shown here. The three earth electrodes X, P and C are in line.

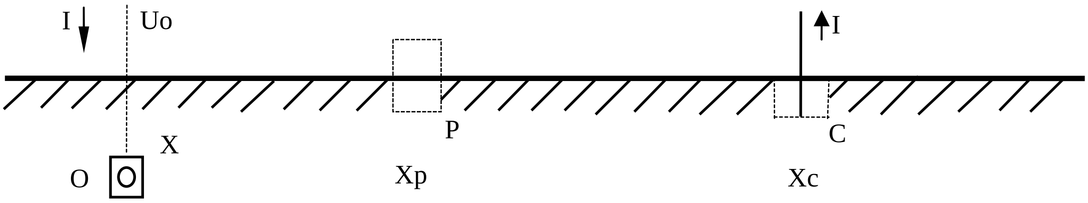

Figure. A.1: Earth electrode layout

It is supposed that the electrodes X and C are ideal hemispheres and that the earth is homogeneous. The potential in the earth related to the remote earth at the point of abscissa Xp is expressed as:

$$U(X_p) = \frac{\rho I}{2\pi X_p} - \frac{\rho I}{2\pi (X_c - X_p)} \tag{1.1}$$

If R is the earth's resistance of the earth electrode X, the potential of the electrode is:

$$U_o = U(0) = RI - \frac{\rho I}{2\pi X_c} \tag{1.2}$$

The difference of voltage measured is:

$$V = U_o - U\left(X_p\right) = RI - \rho I\left(\frac{1}{2\pi X_p} - \frac{1}{2\pi\left(X_c - X_P\right)} + \frac{1}{2\pi X_c}\right) \tag{1.3}$$

$$V = RI - \frac{\rho I}{2\pi}\left[\frac{1}{X_p} + \frac{1}{X_c} - \frac{1}{X_c - X_p}\right] \tag{1.4}$$

The condition V = RI is satisfied for Xp = 0.62 Xc.

It must be emphasised that the calculation makes the assumption that the equipotential surfaces around the electrodes are hemispheres, but this is true only at a distance from the electrode of about five times the electrode size or greater.