ERA REPORT 97-0533
Earthing Solutions, Standards, Safety & Good Practice
PP 3.2.1 - 3.2.15

EXPERIMENTAL METHODS FOR THE EXAMINATION OF SUBSTATION EARTHING SYSTEMS

Th. Aschwanden, R. Bräunlich
FKH, Fachkommission für Hochspannungsfragen, Switzerland

AUTHOR BIOGRAPHICAL NOTES

Thomas H. Aschwanden received his Dipl.-Ing. and Ph.D. degrees in electrical engineering from the Swiss Federal Institute of Technology (ETH) Zürich in 1978 and 1985, respectively. He joined the Weber Research Institute, Polytechnic University of New York, in 1985 and worked there as a research associate in the field of electrophysics and pulsed power technology. In 1987 he became senior assistant to the high voltage engineering group of ETH. Since 1990 he has been the head of the high voltage research commission (FKH) of the Swiss power utilities and industry. The research activities of Dr. Aschwanden include electrophysics, high voltage technology, electromagnetic compatibility, pulsed power, dielectric materials and insulation diagnosis, lightning protection, on-site testing of high voltage apparatus and systems. He is a member of IEEE, CIGRE and the Swiss Electrotechnical Association (SEV).

Reinhold H. Bräunlich received his Dipl.-Ing. degree in electrical engineering in 1982 and his Ph.D. in 1993 from the Swiss Federal Institute of Technology (ETH), Zürich. After a short period as a development engineer with BBC Brown Boveri & Cie., he joined the high voltage engineering group of ETH in 1983. Since 1991 he has been with the high voltage research commission (FKH) in Zürich, where he works in the field of on-site high voltage testing. He is a member of IEEE and the Swiss Electrotechnical Association (SEV) and therein a member of the Power Society (ETG).

ABSTRACT

Experimental methods for the judgement of large earthing systems of high voltage substations including AC fault current injection are described. For the verification of the requirements for personal safety it is usually sufficient to assess the earthing voltage of a substation as well as adequately selected samples of touch voltages. An important requirement for reliable measurements of touch voltages in operating substations is the discrimination against disturbing signals originating from the line currents. It is shown, that interfering signals may easily be suppressed by using asynchronous fault current injection with a frequency different from line frequency (50 Hz). Evaluation of the current distribution in the event of an earth fault provides further insight into the condition and state of large and complex earthing systems.

1 Introduction

Experimental examinations of earthing systems serve first of all as a means to test personal and technical safety in case of an earth fault. The goal of so called "earthing measurements" is the judgement of the efficiency of an earthing system. Within the area of influence of electric installations, no immoderate values of earth potential differences or earth currents, which might endanger living beings or technical installations, must occur. For the case of an earth fault, the admissible touch voltages on accessible metal objects are limited. In Europe, these limits are specified in national standards usually laid down as a voltage-time-curve (see Figure 1). These definitions are based on the sensitivity of the human body to AC currents; the limiting values differ somewhat from country to country [8...12].

At the moment, efforts are being made to harmonise the rules for earthing installations as part of the CENELEC standard *"Power installations exceeding 1 kV AC"*. A preliminary version is already available [1].

In addition to safety matters, the judgement of an earthing situation should also include operational viewpoints. Here, examinations on mutual disturbances between different adjacent installations and overload of conductors in special operational situations are in the centre of interest. Another important question is the minimisation of energy loss during operation due to closed (earthing) current loops.

For a complete judgement of a substation earthing, not only the earthing system but also the situation of the grid, the types of power lines and earth connections to other technical installations in the vicinity of the substation have to be considered. It has to be kept in mind that usual touch voltage examinations at electric power installations can only be carried out by spot checking. The selection of the test points presumes an exact knowledge of the whole situation of the examined substation.

The measuring methods presented here are restricted to earthing conditions at power frequency (50 Hz, 60 Hz or traction systems at 16.7 Hz). More precisely, the earthing installations are examined with regard to earth fault situations that are simulated by an artificial, large earthing current loop (see Figure 2). This experimental viewpoint is also the basis for the design of an earthing system, so that dimensioning can be verified directly. In case of an earth fault, temporarily, a high current flows through the earthing system into the soil. The distribution of the fault currents causes a (transitory) rise in potential of the earthing system, which is responsible for the step and touch voltages to be examined and judged.

An important part of an earthing system analysis is the evaluation and interpretation of the measured values. Unexpectedly high or inconsistent touch voltage values can often not readily be explained. However, knowing further data and information about the examined system (i.e. geometrical disposition of the earthing grid, potential and current distribution) helps to come to a conclusion and to suggest remedial measures.

Finally, the experimental examination of an earthing system should generally provide information on weak points and data for a further optimisation of the earthing arrangement.

2 Injection of earth fault current - formation of earth fault current loop

The experimental examination of the potential and current distribution of an earthing system is essentially based on the current-voltage-method [1], [2]. For this purpose, a defined earth fault current I_E is injected into a defined earth fault current loop, which comprises the earthing system to be examined. The experimental earth fault current is generated by a single-phase AC current source or by an impulse current source. Usually the current amplitudes used for fault current simulation are limited by circuit impedance and source: typical values in the 220kV- or 400kV-grid are 100 - 200 A (AC).

For large earthing systems the earth fault current loop is usually formed by an overhead line or a cable which has to be taken out of operation and earthed in a neighbouring substation (auxiliary or reference earth, see Figure 3). Generally, the examined substations remain in operation, and therefore, interference from service currents (i.e. 50 Hz) and their harmonics have to be expected in all earthing system measurements. The distance between the two substations used to form the earth current loop has to be sufficiently large (more than 1 km), so as to exclude any mutual influence of the earthing systems. The phase conductors of the power line used to feed the experimental earth fault current are often connected in parallel to reduce the impedance of the loop (zero sequence impedance).

The potential of the earthing system under test rises to the earthing voltage U_E by the action of injecting the earth fault current (see Figure 2). The earth potential decreases to lower values with increasing distance from the boundary of the earthing system. Any objects within the 'hot zone' around the substation area encounter a potential gradient, and therefore, show a voltage difference with respect to the surroundings. With appropriate voltmeters, these voltage differences can be measured as touch or step voltages[1].

The experimental earth currents circulating from one substation to the other are not only flowing through the soil but also through cable sheaths and ground wires of overhead lines, as already men-

[1] A 'hot zone' is also established around the substation used for auxiliary (reference) earthing. Therefore, earthing measurements can be performed on both substations forming the experimental earth fault current loop (Figure 3).

tioned in the introduction. Other extended conducting structures such as tube ducts, railway lines or Telecom lines conduct a part of the fault current as well. The assessment of these conductor-bound currents is also an integral part of an earthing system examination.

Measured results (touch and step voltages, earth conductor currents) are subsequently linearly extrapolated to the maximum earth fault current of the examined installation. This maximum earth fault current of a high voltage substation with solidly earthed neutrals is usually produced on the occasion of a line-to-earth fault on a bus bar and is dependent on the state of the grid.

For the injection of the earth fault current I_E a current source with an ampacity of a few tens to a few hundreds of amperes is required for large earthing systems of high voltage substations or power plants. The measurements described in this paper were performed either with a 100 kVA diesel generator or with an electronic frequency converter with a power of 50 kVA. For proper matching with the impedance of the experimental current loop, a special transformer is used. To cope with the large reactive power required to energise long earth fault current loops, a capacitive reactor bank can be switched in parallel to the output of the transformer, thus allowing the compensation of a maximum reactive power of 550 kVAr. The electronic frequency converter and the transformer are designed to inject currents at frequencies from 12 Hz to 500 Hz, enabling for example the study of the frequency dependence of the impedance to earth, or working close to railway frequency (i.e. 16.7 Hz in Switzerland).

3 Problems with measurements

Besides interference problems, there are some fundamental problems with earthing measurements which can cause significant uncertainty in the interpretation of the measured quantities. Additionally, there are some inherent limitations of the reproducibility of such measurements. The problems responsible for these inconveniences are listed and, where applicable, commented in the following. Some of these open problems can be overcome by using a standardised measuring procedure. Special aspects of these measurement procedures should be examined with experiments on earthing systems:

1. The *specific resistance of the soil* is not constant in time mainly because of different humidity and temperature. It is subject to a variation of roughly one order of magnitude.
2. Due to the *compression of the soil*, the resistance to earth of newly laid earth conductors is slowly reduced, a process which can take many months .
3. Earth fault currents do not produce a spherical DC conduction field around the earthing system because of the *inhomogeneous soil conductivity*. For geological reasons, the soil conductivity decreases with depth, which leads to surface-bound earth currents. Neglecting AC effects, the current density and the resistive electric field of a single earth electrode decrease with the square of the distance from the electrode for small distances, and almost linearly for larger distances. For simplicity, we assume an earth electrode with a boundary of a half-sphere for the following considerations. The earthing voltage U_E is the integral of the resistive electric field strength $E_E(r)$ taken from the boundary of the earthing system ($r = r_o$) to an infinitely large distance.

$$U_E = \int_{r0}^{\infty} E_E(r)\,dr = \int_{r0}^{\infty} E_0 \cdot \left(\frac{r}{r_0}\right)^{-k} dr \qquad 1 < k < 2 \qquad (1)$$

E_E	resistive electric field strength around the earthing system [V/m]
r	distance from centre of earthing system [m]
r_o	radius of earthing system [m]
E_o	resistive electric field strength on the boundary of the earthing system [V/m]
k	exponent of the decreasing potential function depending on geological factors

The earthing voltage U_E and the impedance to earth $Z_E = U_E / I_E$ of the installation depends upon the distance to which the integral (1) is evaluated (in practise this can never be infinity). In the limiting case of a current propagation on the surface of the soil ($k = 1$), the impedance to earth would even become infinitely large (see also [6], Chapter D, Clause f).

4 The problem of the uncertain definition of the impedance to earth described above (point 3) becomes even more complicated if we consider the fact that earth fault currents are AC currents which are subject to current displacement (skin effect) in the soil (see Figure 5). Alternating currents in the soil do not spread out very far, but they stay as close to the loop of the fault current as possible. AC currents do, therefore, not propagate in the shape of the electric field of a static dipole (Figure 5, top), but in a straight corridor of a width of some 100 m in the direction of the line feeding the fault current (Figure 5, bottom). The result is a strongly *asymmetrical earth current distribution* around the earthing system, particularly since the experimental fault current is fed only from one side.

The *penetration depth* δ in the soil of the magnetic field or the current yields quantitative information on the propagation of earth currents.

$$|\delta| = \sqrt{\rho / \omega \mu_0} \qquad (2)$$

δ	penetration depth of earth current [m]
ρ	specific resistance of soil [Ωm]
ω	angular frequency of earth current [s^{-1}]
μ_0	magnetic permeability of vacuum [$4\pi \cdot 10^{-7}$ Vs/Am]

Penetration depths δ between 150 m and 1500 m result from typical values of the specific resistance ρ of the soil ranging from 10 Ωm to 1000 Ωm at 50 Hz. From these statements it can be concluded that the measured impedance to earth of an installation does not only depend upon the evaluation distance (according to point 3), but also upon the direction of the measured voltage profile with respect to the feeding line, and on the frequency. Therefore, particularly large substations with dimensions in the order of magnitude of the penetration depth δ, i.e. some 100 m, possess an earth current distribution which strongly depends on the direction of the fault current feeding line. Furthermore, also the measured touch and step voltages strongly depend on the line chosen to feed the earth fault current. This fact complicates the evaluation of the earthing situations of large installations if only one configuration of feeding line has been examined.

5. Often there is no clear confinement of the earthing system because the installation consists of several remote parts (e.g. a terminal pole of a overhead line) which are connected by earth conductors (over and under ground). For this reason, the impedance to earth is often not clearly defined. Finally, because of the above mentioned remote parts of an installation, the results of the measurements of touch and step voltage depend strongly on the *direction of the fault current feeding line*.

The above mentioned aspects clearly demonstrate that the real earthing situation of any installation can only be simulated by injecting experimental currents via all earth fault current feeding lines. For practical reasons, this kind of simulation cannot be applied to a standard examination. Therefore, to achieve reproducible results, it is important to use a *standardised procedure* for the examination of earthing systems of larger installations. Today, though, there is a lack of such guidelines or recommendations.

4 Elimination of interference

High voltage substations and large power generation plants usually remain in operation during earthing system measurements. Therefore, by ohmic or inductive coupling, power frequency interference can be coupled into the experimental current loop or any measuring loop. This interference may lead to substantial errors in the measurement if it is not eliminated properly [4, 5]. Besides mains frequency interference (50 Hz, 60 Hz, 16.7 Hz) also its harmonics and DC currents have to be considered. The following techniques are widely used to suppress interference (see also [1],[2],[3]):

- beat method
- on/off method
- polarity reversal method
- vector voltmeter, synchronous rectifier, lock-in amplifier
- choice of a fault current frequency different from mains frequency, filtering of interference signals

A summary of the advantages and disadvantages of the different methods for interference elimination is given in Table 1.

The *beat method* uses an experimentally injected earth fault current with a frequency slightly different from the operating frequency of the installation (deviation smaller than 1 Hz). A beating is produced by superposition of the mains frequency interference voltage U_s and the measuring voltage U_m, which leads to an oscillation of the read-out of the voltmeter between a maximum value U_{max} and a minimum value U_{min}. The measuring voltage U_m can be calculated according to Figure 6. It is evident that the accuracy of this method depends on the skill of the person who carries out the measurement and on the time constant of the voltmeter.

The *on/off method* employs a mains frequency fault current which is switched on and off periodically. The method is called *polarity reversal method* if the two phases of the current source are reversed before each on-cycle. All measurements are carried out in the on- and off-state (U_s) of the current source; in the case of the polarity reversal method, the measurement is performed at both polarities (U_1 at positive and U_2 at negative polarity) and in the off-state (U_s). It has to be mentioned that the polarity reversal method only delivers reasonable results if the experimental current is absolutely in phase with the operating frequency of the installation. Moreover, the interference has to remain constant during the three readings at one particular location.

Whereas the on/off method gives only an upper limit for the measurement error, the polarity reversal method can yield an unambiguous relation between the three measured values and the voltage U_m caused by the injected current (see Figure 7). Recently, a computer supported on/off method which allows an efficient suppression of interference has been presented [5].

In the last few years, the authors have gathered a lot of experience with all of the methods mentioned except for the polarity reversal method. The most effective elimination of interference was achieved with the use of a fault current with frequency different to mains frequency. In some cases this method is used in combination with synchronous rectifiers (i.e. lock-in amplifier), thus resulting in a very high signal-to-noise ratio.

The experimental earth fault current is either produced with a diesel generator or a static frequency converter. For substations operating at 50 Hz, a frequency of the injected current of 70 Hz is usually chosen. For installations of the Swiss railways (SBB), which operate at 16.7 Hz, measurements are generally performed between 12 Hz and 24 Hz. This deviation from the operating frequency of the installation under test allows a very simple and effective separation of the experimentally injected currents from earth currents produced by the operation of the plant. The measurements of touch and step voltages are carried out with a special voltmeter including highly selective notch filters for 50 Hz and 16.7 Hz.

For the measurement of earth current distributions, lock-in amplifiers and synchronous rectifiers have been used for the very sensitive measurement of amplitude and phase of partial earth currents. This sophisticated instrumentation enables the accurate assessment of large high voltage installations at only moderate injected currents (tens of amperes). However, the transmission of a reference signal from the current source to the place of measurement is a prerequisite for these techniques.

Method	Frequency	Measurement	Advantages	Disadvantages
1 Beat method	Deviation from mains frequency <1 Hz	Measuring time a few seconds, without filters	Measurement close to mains frequency	Evaluation not always unambiguous
2 On/off method	Arbitrary	2 measurements, without filters	Simplicity	No minimisation, but only estimation of error
3. Polarity reversal method	Mains frequency	3 measurements, without filters	Unambiguous determination of measuring voltages, measurement at mains frequency	No elimination of harmonics, 3 measurements needed
4 Vector voltmeter lock-in amplifier	Arbitrary	One measurement with dedicated instrument	Suppression of all kinds of interference possible	Requests reference signal from exp. current source
5. Filtering of interference	Deviation from mains frequency >10 Hz	One measurement with filters	Suppression of all kinds of interference possible	Measuring frequency not identical to mains frequency

TABLE 1 Compilation of methods for the suppression of interference and their advantages and disadvantages.

5 Determination of voltage profiles and impedances to earth

Earthing voltage profiles are a valuable tool for the further assessment of earthing systems. An earthing voltage profile is determined by measuring potential differences between the earthing system of the plant (reference) and metal pike electrodes which are inserted into the soil at defined positions (e.g. at 1 m, 5 m, 10 m, 100 m distance from the boundary of the plant) in a given direction.

Figure 8 shows the result of such an earthing voltage profile measurement at different frequencies of the injecting current. The frequency-dependence of the potential profiles is due to displacement effects of the earthing currents (see also section 3, paragraph 4).

From the shape of the voltage profile, the 'hot zone' around the installation and the effectiveness of surface potential control measures can be verified. Particularly the voltage gradients are clearly visible in this representation. The existing step voltage can be taken as voltage difference from the measured voltage profile.

The effective impedance to neutral earth of an installation can be determined by evaluating the voltage profile along a sufficiently long distance. The value of the impedance to earth Z_E is defined as the ratio of the maximum (asymptotic) value U_E of the voltage profile to the earthing current I_E which produces this voltage:

$$Z_E = U_E/I_E \qquad (3)$$

An important reason for the measurement of voltage profiles is the question of the magnitude of the earthing voltage U_E. If U_E is smaller than the maximum permissible touch voltage, the measurements can be stopped, i.e. no touch and step voltages have to be measured. Field experience confirms that the voltage profile strongly depends on the direction of the profile relative to the earth fault current feeding line, as has been stated in a previous chapter. Reproducible results may be obtained if an angle of about 90° between the direction of the profile and the feeding line is maintained (Figure 5b) and if no other conducting structures are in the vicinity of the profile.

If all of these conditions are fulfilled, the voltage along the profile reaches saturation caused by current displacement (skin effect) after a few hundred meters. Therefore, a clear and meaningful value for the 'apparent' earthing voltage U_E can be determined. The measurement of at least two profiles is always recommended since this allows the reproducibility of the results to be checked.

6 Measurement of touch, step and differential voltages

Touch voltages are measured between the point of contact and the (local) earth in a distance of 1 m of the metal object (Figure 1). To contact the earth, a pike electrode (serving as reference potential) is driven into the soil to a depth of a few centimeters. In certain cases, differential voltages between two objects are measured as well if they are next to each other and if they are not electrically connected.

To perform earthing measurements, a dedicated selective voltmeter was developed (design by FKH). This instrument includes selectively switchable band stop filters for 50 Hz and 16.7 Hz and allows direct readings to be taken of voltages from 10 mV to 1000 V. The filters suppress interference from 50 Hz or 16.7 Hz by about 40 dB, enabling the measurement of signals in the millivolt range. Two readings are usually taken for each measurement position: in the first measurement the voltage is measured directly over the high input impedance of the active filter; in the second measurement the input of the filter is loaded by 2 kΩ. The first measurement yields the voltage actually present at a certain position (i.e. the prospective touch voltage [1]), whereas the second one provides the voltage which would appear if the measuring position was loaded with the impedance of the human body. The voltage values taken with the 2 kΩ-load are usually taken for further analysis.

The effectiveness of the earthing system and touch and step voltages appearing in case of an earth fault have to be assessed and summarised in a report. Typically, the touch and step voltages are represented in the form of bar graphs as shown in Figure 9 and in the map in Figure 10. The values of the measured voltages are linearly scaled to an earth fault current of 1 kA or to the maximum earth fault current of the installation.

Countermeasures have to be taken if inadmissible touch or step voltages have been recorded. The following countermeasures are often taken to prevent high touch or step voltages or to reduce their danger for people:

- laying an additional surface layer (asphalt, crushed rock)
- surface potential control with additional earth electrodes
- coating the metal structure with an insulating paint
- putting up of warning signs
- reducing protection trip time.

7 Determination of earthing current distribution

The determination of the earthing current distribution provides answers to the following questions:

1) Are all of the earthing conductors intact and of low resistance?
2) Are there power or signal cables which are loaded by excessive earthing currents (sheath currents) in case of an earth fault, which may lead to perturbations, overvoltages or even thermal overload of a cable?
3) Are there unwanted connections between insulated conductors on zero potential and earth (open cable sheaths, separated earth electrodes)?

A systematical determination of the current distribution of all conductors which are in touch with the earthing system of the installation or which are used for its earthing, respectively, is recommended for the assessment of the effectiveness of earthing systems. Table 2 lists the relevant types of conductors.

If all of the current shares in Table 2 are registered in magnitude and phase and if there are no other connections between the surrounding earth and the earthing system of the installation, the vectorial sum of all registered currents must be equal to the injected current. By means of this measurement, the distribution of the earth fault current can be assessed. Generally, a substantial fraction of the earthing current flows directly from the earthing grid into the soil. This fraction cannot be measured and appears in the 'balance sheet' as the non-assessed *remaining current*. An example of an earthing current 'balance sheet' is shown in Figure 11.

• connections to earthing electrodes and earthed structures • earth wires of overhead lines • earthed sheaths of power cables • low voltage cables • control and signal cables with earthed sheaths • telephone cables • conducting water pipes and gas conducts

TABLE 2 List of types of conductors to be considered for the evaluation of the earthing current distribution.

The measurements of earthing current shares are performed by means of prong-type ampere meters, and for conductors of larger diameter (e.g. high voltage cables, pipes and high voltage poles with diameters up to 1 m) with dedicated Rogowski coils (see Figure 12). To avoid interference, the voltage across the burden of the current transformers has to be transmitted by means of twisted and shielded cables (twinax-cable). As in the case of touch and step voltages measurements, band stop filters can be used to suppress 50 Hz and 16.7 Hz interference (see section 6).

The determination of the phase of earthing current shares in earthing conductors or cable sheaths requests a reference signal which has to be transmitted from the fault current generator to the place of measurement. For distances up to about 100 m, this reference signal is transmitted by means of a twinax cable to the place of measurement, where the phase shift between this reference and the earthing current share is determined. For the transmission of reference signals over larger distances (up to 1 km), signal transmission by radio was developed. A short synchronisation impulse is transmitted by radio (FM 434 MHz) at each detected zero crossing of the injected current, hence allowing the determination of the phase shift of the measured current. Assuming that the phase shift of the reference channel has been balanced prior to the measurement, the phase angle can be determined with an uncertainty of ±5°.

The earthing current shares are divided into a real and an imaginary part, permitting their vectorial summation (Figure 11). The component of the current in phase with the injected current is called the real part, whereas the component shifted by 90° is the imaginary part.

7.1 "Indirect" measurement of earthing currents in earth wires of overhead lines

Earthing current shares in earth wires of overhead lines can be assessed by measuring the magnetic induction B due to this current. This indirect assessment has the advantage that currents in hardly accessible earth wires can be measured on ground level by means of a loop antenna. Again, mains frequency interference can be separated from the injected current (e.g. 70 Hz) by means of band stop filters.

The principle of the 'indirect' earthing current measurement is shown in Figure 13. The earth wire current I_T generates a magnetic induction B, which induces the voltage U_{ind} in the loop antenna. This induced voltage is amplified and integrated in time, the resulting voltage U_{meas} is proportional to the current flowing in the earth wire and inversely proportional to the distance d to the current path.

The integrator can be calibrated in such a way that the current I_T can be calculated according to

$$I_T[\mathrm{A}] = U_{meas}[\mathrm{V}] \cdot d\,[100\ \mathrm{m}] \qquad (4)$$

Even very small currents in the milliampere range can be measured with this method if synchronous rectifiers are used, no matter whether the overhead line is in operation or not.

8 Conclusion

The application of supplementary experimental methods (primarily by measuring the current distribution) results in a much better understanding of the earthing system for the case of an earth fault. The knowledge of the current distribution among all the conductors leaving a high voltage substation or power plant gives information on possibly protracted potentials. It helps to indicate places where high touch voltages are to be expected or supplies explanations for high potential gradients or touch voltages, respectively. A systematic assessment of all earthing currents also helps to detect conductors that carry high current shares and might possibly be overloaded in case of an earth fault.

Attention has to be paid to measuring errors on account of interference with the operational currents and voltages in the examined installation which may be induced inductively or resistively. It has been demonstrated that the choice of a fault current and measuring frequency slightly different from the normal operational frequency of the power network offers refined possibilities to eliminate disturbing interference. Simple notch filters may manage this task successfully. A more complicated but certainly effective method to measure small signals in a noisy environment is the application of a lock-in amplifier (synchronous rectifier). With this method, the badly conditioned measuring signals are compared electronically with a reference signal of the injected fault current.

Due to inherent experimental limitations it is obvious that the examination of an earthing system does not present precision data since the existing measuring methods are not strictly defined and since the results depend on many details of the experimental arrangement (i.e. direction and size of the fault current loop). Thus it is not permissible to judge the earthing system of a HV-substation with kA-fault currents as "sufficient" or "insufficient" on the basis of a few touch voltage values measured. A pivotal problem is that an earth fault may often not be simulated realistically enough. The earthing current distribution always depends strongly on the choice of the power line where the experimental current is fed in. The current displacement by its own magnetic field is one of the most important effects that causes an asymmetrical current distribution and complicates the analysis of the measured potential raise.

The methods for experimental examinations have to be established in such a way that all results are reproducible and that as little scope as possible is left for the interpretation of the measurements. In this respect, precise recommendations for the execution of earthing measurements are highly desirable.

Annotation
The full content of this contribution has already been published in German in the Bulletin of the Swiss Electrotechnical Association [7]. The authors address special thanks to Dr. Thomas Heizmann, FKH, for comprehensive help in doing the translation of this article.

9 References

[1] European Standard Draft prEN 50179 "Power installations exceeding 1 kV AC" European Committee for Electrotechnical Standardization CENELEC, December 1996.

[2] "Erdungen in Starkstromnetzen"; Vereinigung Deutscher Elektrizitätswerke m.b.H. - VDEW, Frankfurt am Main; 3. Auflage, 1992.

[3] A.P.S. Meliopoulos: "Power System Grounding and Transients: An Introduction", Marcel Dekker, New York, 1988.

[4] F. Schwab: "Erdungsmessungen in ausgedehnten Anlagen"; Bulletin SEV/VSE Vol. 71, No 4, (1980), pp. 174.

[5] R. Hoffmann: "Neues Messverfahren zur Eliminierung von Fremd- und Störspannungen bei Beeinflussungs- und Erdungsmessungen"; Elektrizitätswirtschaft, Vol 91, No 22 (1992) pp. 1455.

[6] W. Koch: "Erdungen in Wechselstromanlagen über 1 kV, Berechnung und Ausführung"; Springer Verlag, Zweite Auflage, Berlin, 1955.

[7] R. Bräunlich: "Die messtechnische Überprüfung von grossen Erdungsanlagen"; Bulletin SEV/VSE, Vol. 87, No 23 (1995), pp. 31.

Some national standards for earthing directions

[8] ANSI/IEEE Std. 80-1986:
"IEEE-Guide for Safety in AC Substation Grounding".

[9] CP. 1013: 1065:
"British Standard Code for Practice, Earthing".

[10] IEEE Std. 81-1983:
"IEEE-Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System".

[11] DIN/VDE 0141 / 7.76:
"VDE-Bestimmungen für Erdungen in Wechselstromanlagen für Nennspannungen über 1 kV".

[12] Regeln des SEV 3569-1,2,3: 1985:
"Erden als Schutzmassnahme in elektrischen Starkstromanlagen, Teile 1 bis 3".

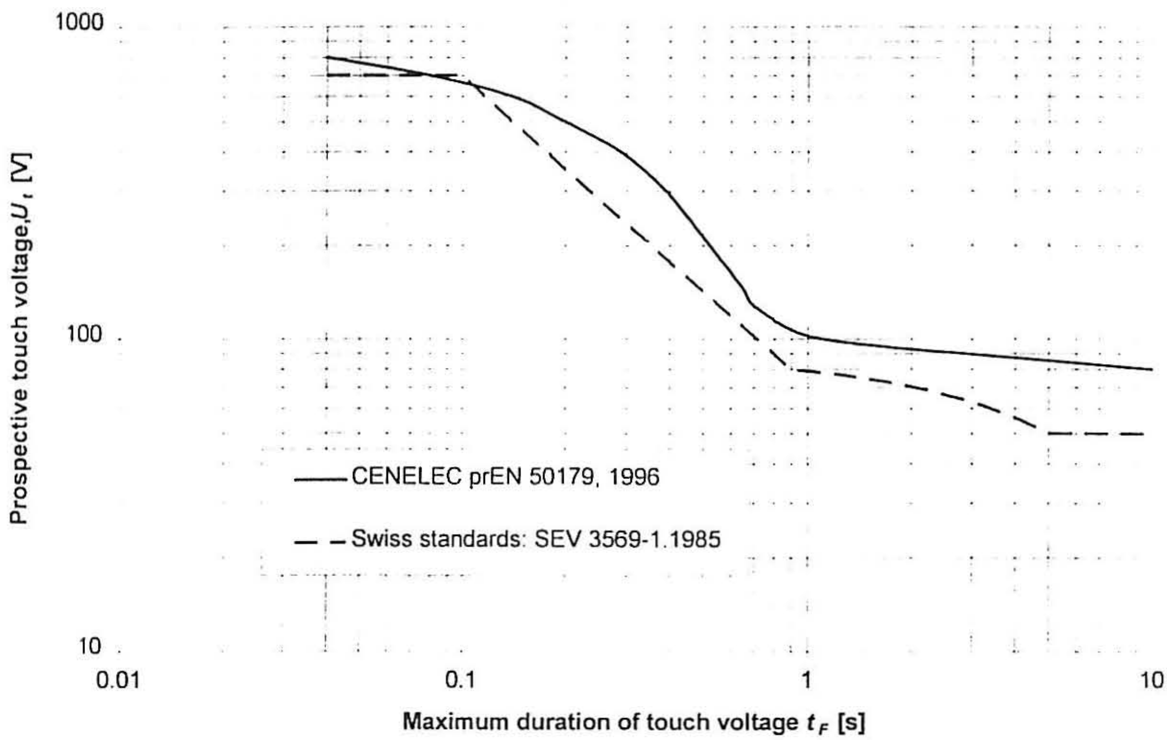


Figure 1 Permissible touch voltages U_{TP} for limited fault current flow duration.

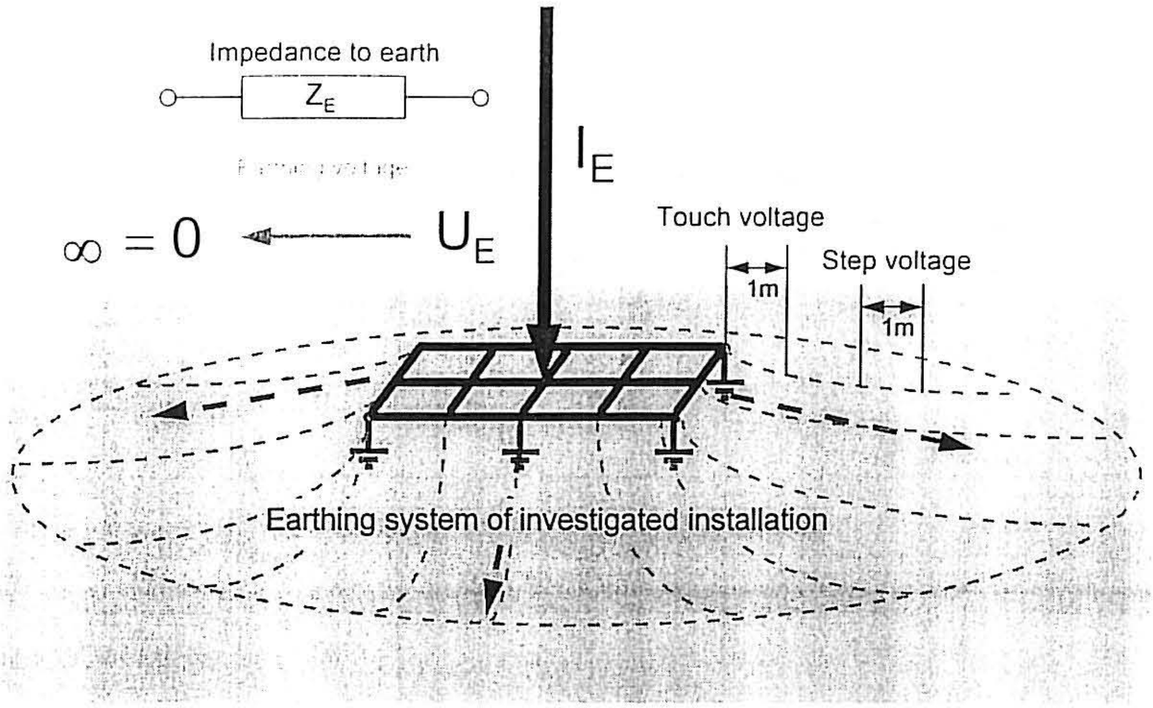


Figure 2 General principle of earthing measurements. An earthing fault current I_E is injected into the earthing system. This current flows through the soil and causes a potential rise U_E in the vicinity of the earthing system. Touch and step voltages are generated in the 'hot zone' around the installation.

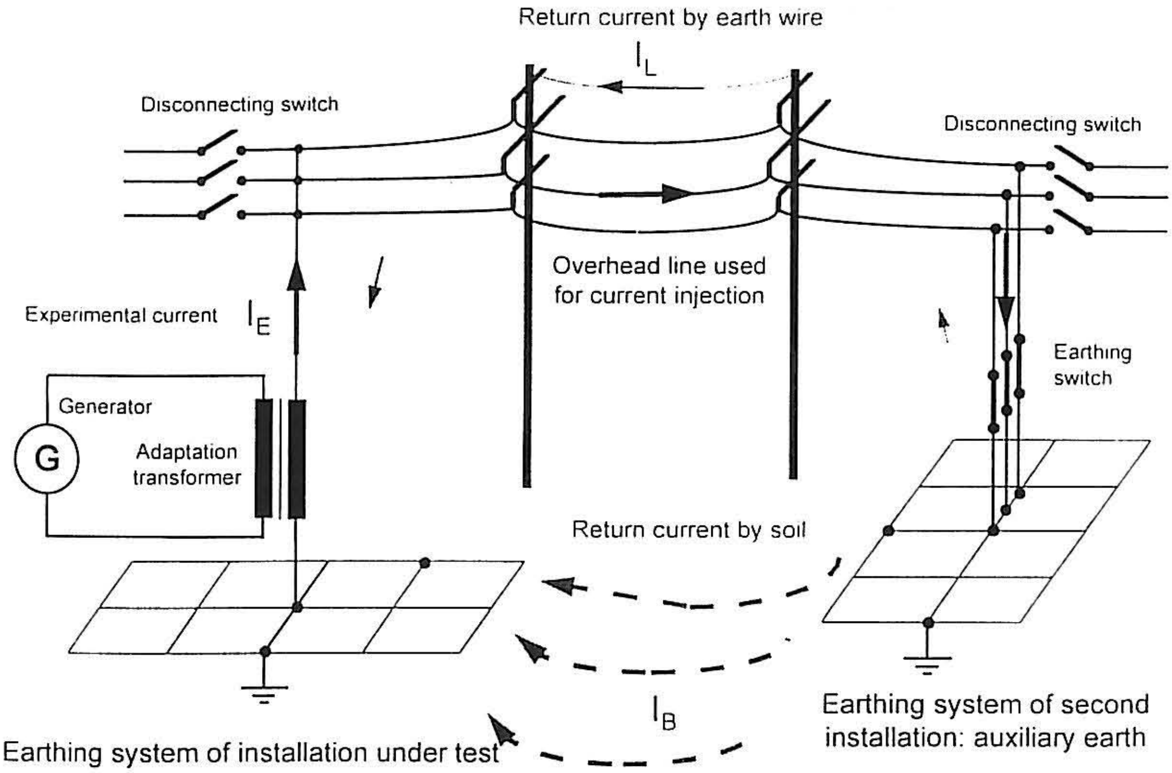


Figure 3 Formation of earth fault current loop by means of two substations and a connecting overhead line. The sum of the return current in the soil I_B and the return currents in the earth wire I_L results in the experimentally injected earth fault current I_E.

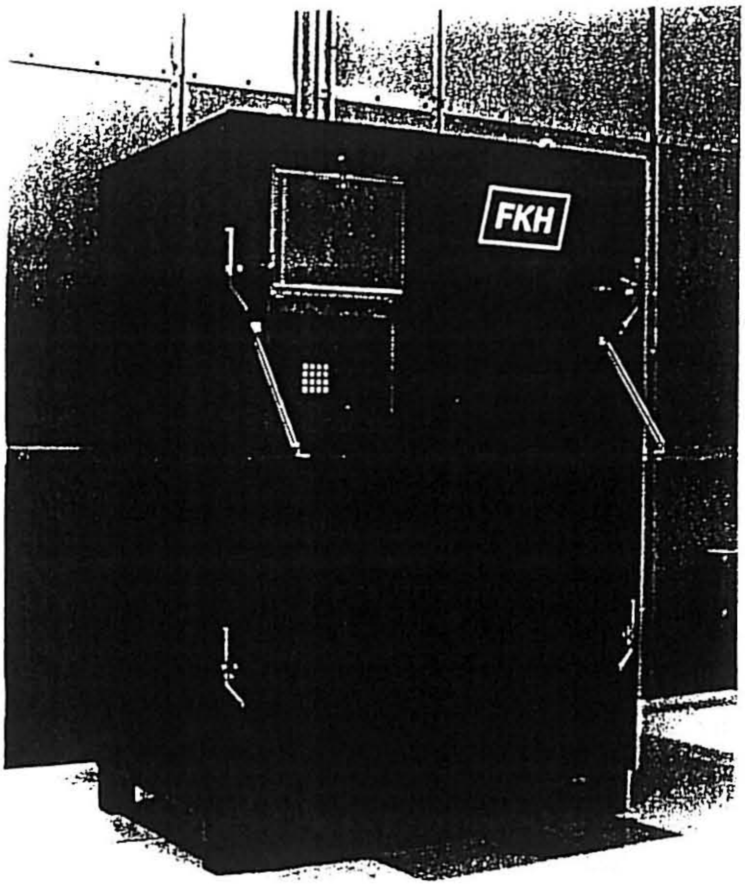


Figure 4 Current source consisting of a frequency-converter (50 kVA) The housing includes auxiliary installations and control circuits.

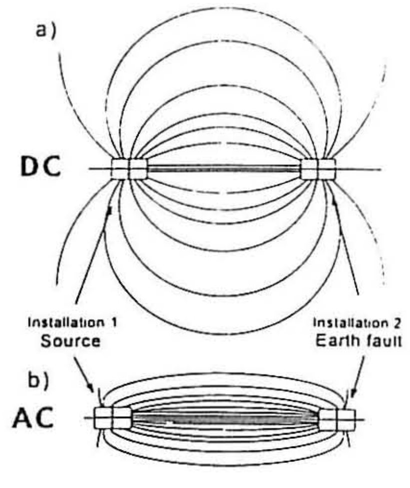
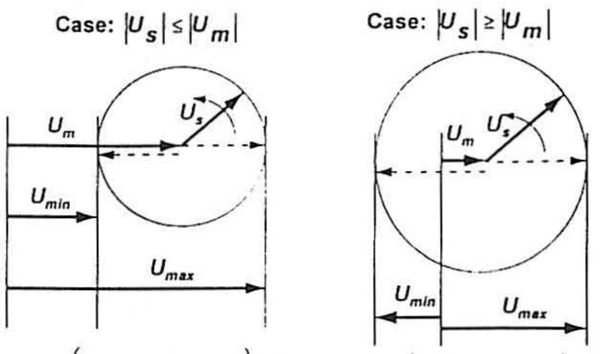
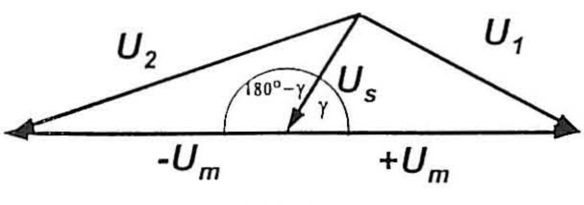


Figure 5 Lines of current in a resistive electric field between two earthing systems (qualitative representation) for both cases: AC top; DC bottom. An earth fault has been set up in installation 2, which is fed over a transmission line from installation 1. Note the concentration of current lines in the case of AC on the side of the line departure.



$U_m = (U_{min} + U_{max})/2$ $\quad$ $U_m = |U_{min} - U_{max}|/2$

Figure 6 Determination of the measuring voltage with the beat method. The measuring voltage U_m is determined by eliminating the interference with mains frequency for the case that the measuring voltage is larger than the interference (left), and for the case that the measuring voltage is smaller than the interference (right).



$\Rightarrow \quad U_m = \sqrt{(U_1^2 + U_2^2)/2 - U_s^2}$

U_1, U_2: Measured voltages $\quad$ *U_s: Interference*

$+U_m, -U_m$: Voltages generated by experimental current

Figure 7 Determination of the measuring voltage with the polarity reversal method. Vector diagram explaining the elimination of mains frequency interference (derivation, see [5]).

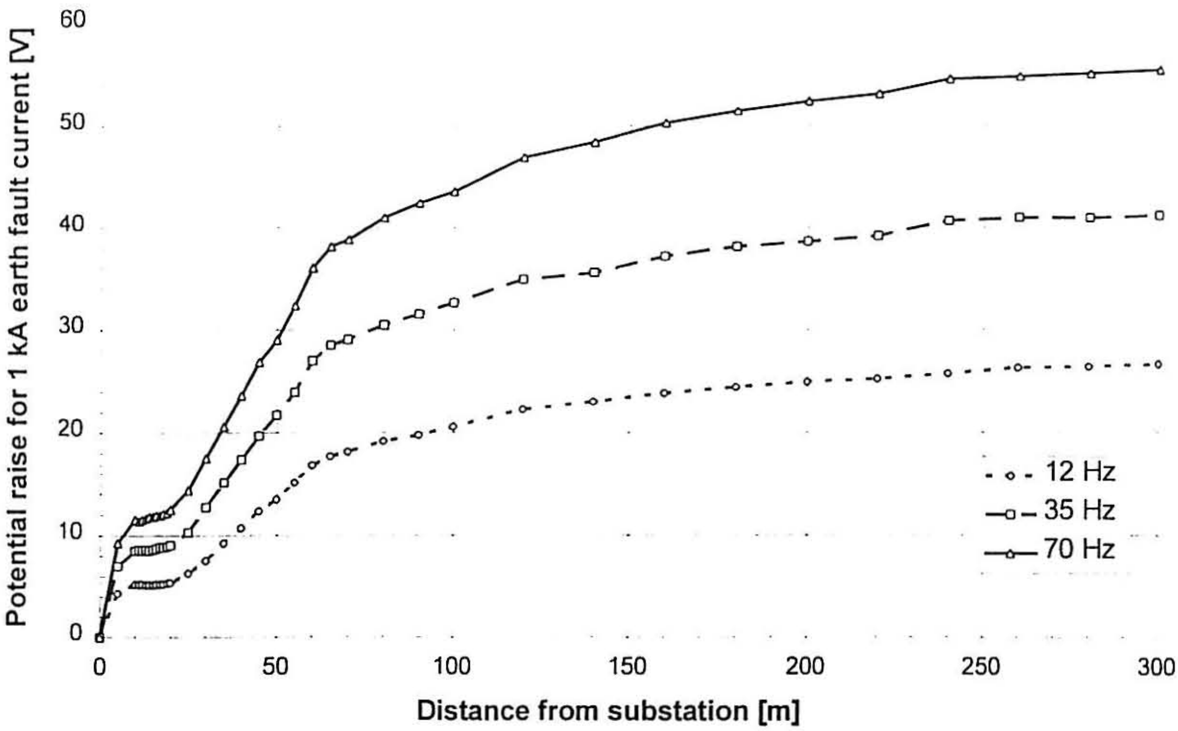


Figure 8 Voltage profiles of a 132 kV-substation measured at three different frequencies of the injecting fault current. The impedances to earth were estimated to 27 mΩ at 12 Hz, 41 mΩ at 35 Hz and 55 mΩ at 70 Hz.

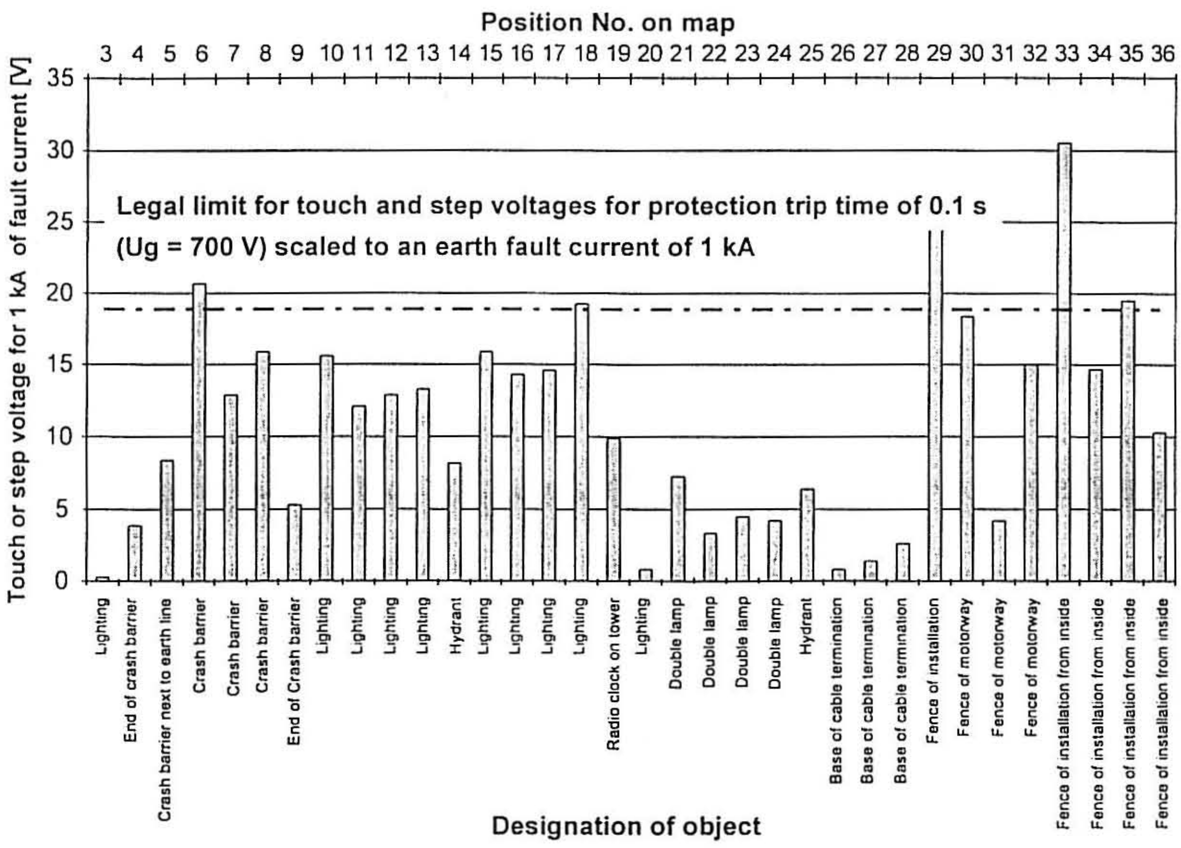


Figure 9 Graphic representation of measured touch and step voltages in the surroundings of a high voltage substation (for measured positions, see Figure 10).

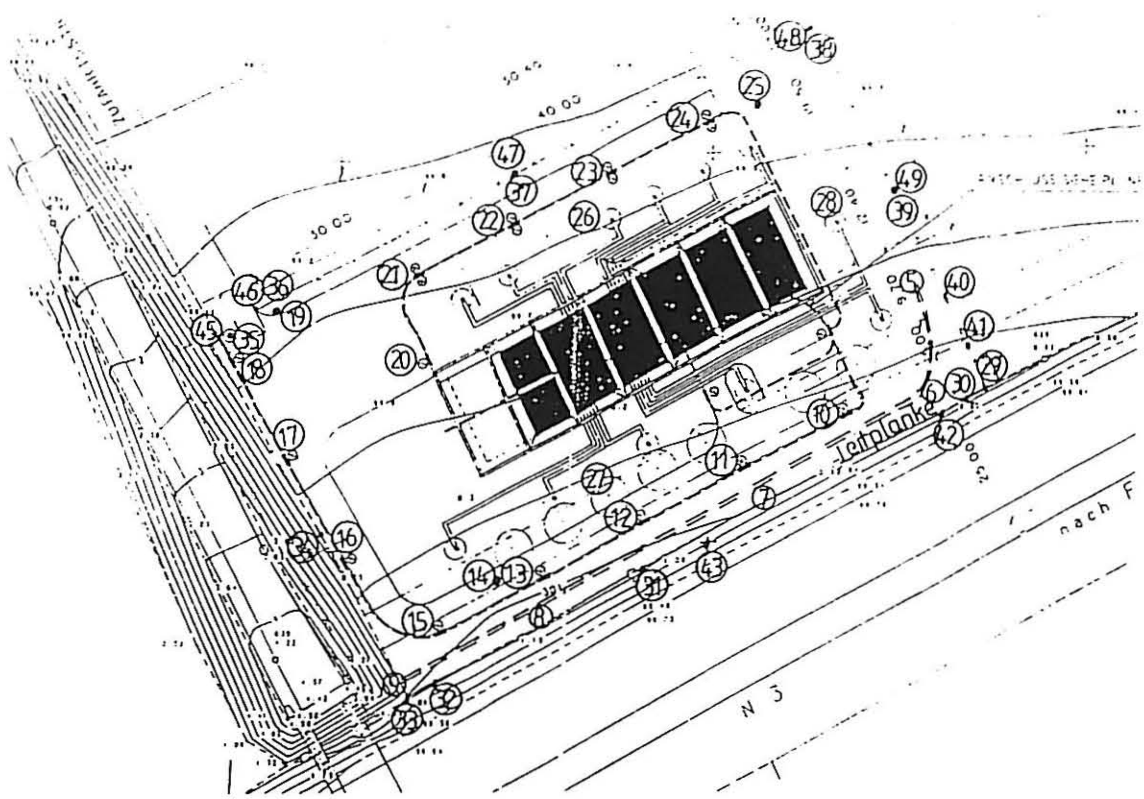


Figure 10 Map of high voltage substation (400 kV-GIS inside building). The locations where touch voltages were measured are marked and labelled with a position number corresponding to Figure 9.

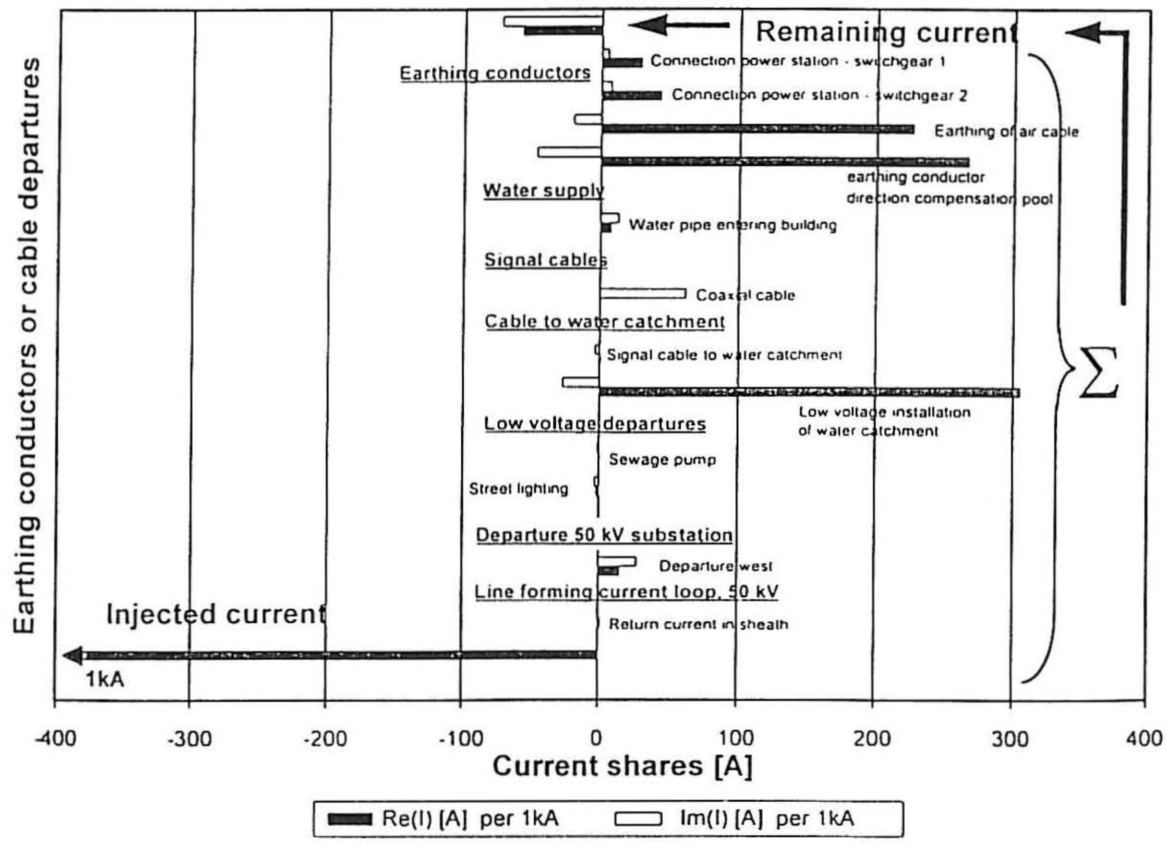


Figure 11 Example of a 'balance sheet'. Vectorial summation is required because of substantial phase shifts between the different shares of the earthing current.

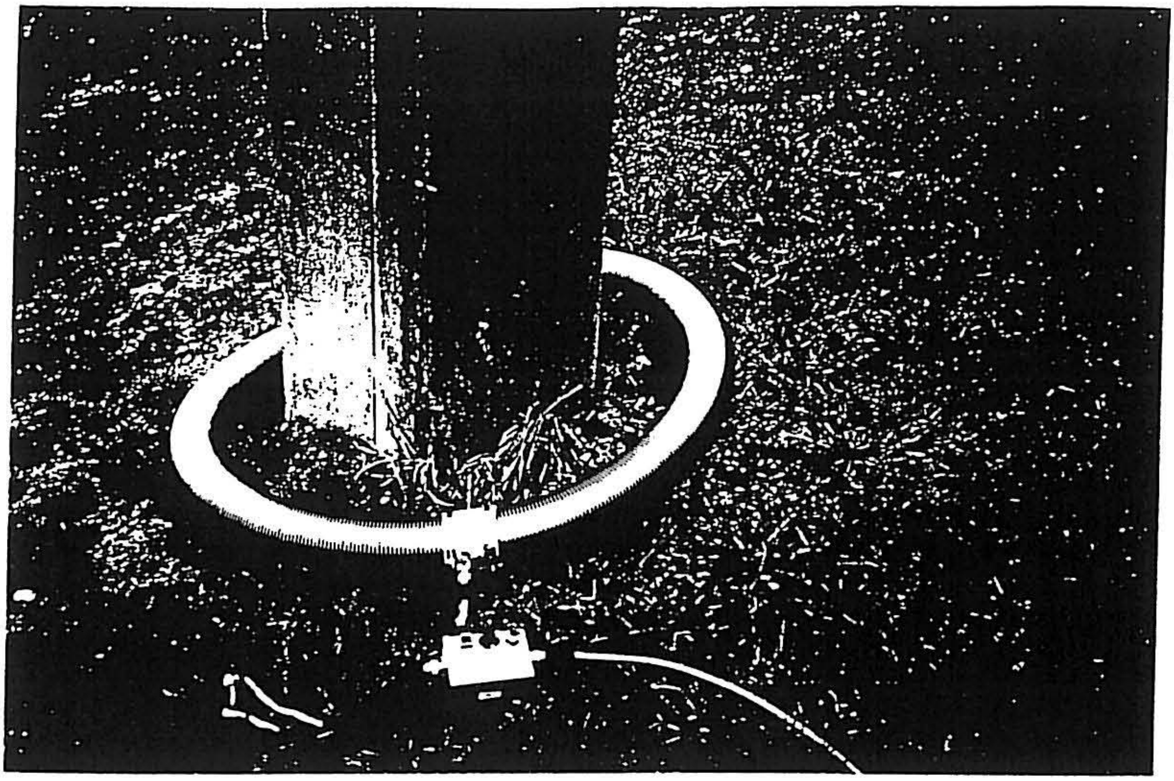


Figure 12 Measurement of a current share in a pole of an overhead line (termination of a high voltage cable).

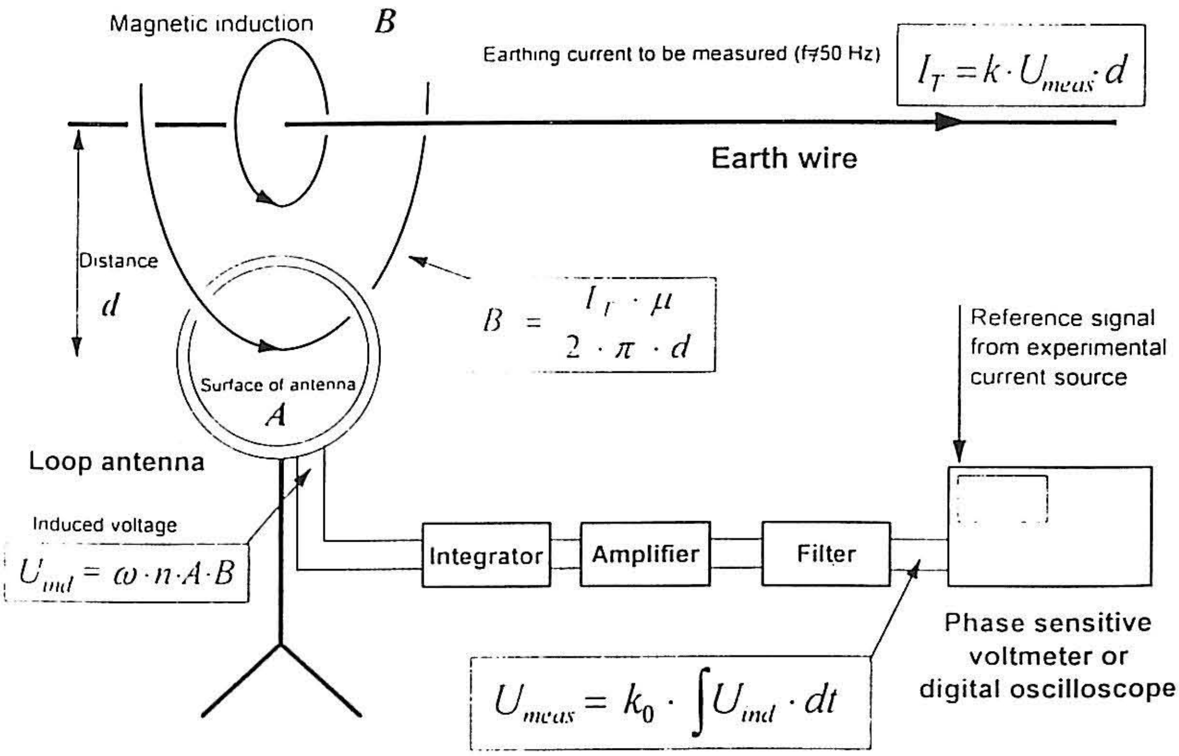


Figure 13 "Indirect" determination of earthing current shares in ground wires of overhead lines