MODELLING OF GROUNDING SYSTEMS FOR BETTER PROTECTION OF COMMUNICATION
INSTALLATIONS AGAINST EFFECTS FROM ELECTRIC POWER SYSTEM AND LIGHTNING

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INTRODUCTION

The operational safety and proper functioning of electric systems is influenced by their earth terminations. Grounding systems serve two purposes: firstly, their task is to disperse fault currents into the earth, which can be evoked either by internal or by external sources, such as lightning or fault in electric power system. Secondly, grounding systems create a reference potential for all electric and electronic apparatus. Transient voltages between points and disturbances conducted across the grounding systems may be a source of malfunction and destruction of components in electrical connection.

Guidelines for the design of such grounding systems are usually based on their low frequency resistances. This is essentially because such resistances to ground may be easily measured or estimated analytically. However, high frequency performance of the grounding systems is essential for the reduction of transient voltages that may appear at terminals of connected sensitive electronic systems in case of impulse excitation, especially related to lightning.

Another aspect of grounding systems modelling is their possible complexity. Although there are simple formulas for simple grounding systems, many practical problems involve complex grounding connections and simulation of different wiring cases requires comprehensive computer software.

This paper addresses three important issues in modelling of grounding systems: modelling of high frequency and transient behavior, of complex and extended grounding systems, and use of software methods.

First, modelling of frequency dependent and transient behavior of grounding systems is considered. When simple grounding arrangements are considered then simple steps for improved design for better transient performance may be followed. In cases when they are subjected to fast fronted current impulses, that is, with high frequency content, generation of large peaks of the transient voltages between excitation point and neutral ground during the rise of the current impulse is possible. Described design procedures are aimed at reducing such excessive transient voltages. More complex grounding arrangements may be optimised using suitable computer software.

Next, modelling of very complex grounding systems is described. As an example, protection against dangerous voltages between telephone subscriber lines and local ground near high voltage substations due to ground potential rise in case of ground faults is analysed. A computer model of the substation grounding system and connected and near buried metallic structures in urban environment is used for estimation of the ground potential rise zone of influence on the subscription wire-line installations.

Finally, computer software method for analysis of low and high frequency and transient analysis of grounding systems of arbitrary geometry are described.

MODELLING OF FREQUENCY DEPENDENT BEHAVIOUR OF GROUNDING ELECTRODES

It is accepted that the dynamic behaviour of grounding systems at high impulse currents generally depends on two different physical processes. The first one is the non-linear behaviour of soil due to soil ionisation in the immediate proximity of the grounding electrodes in case of high current impulses, and the second is the propagation of electromagnetic waves. It is usually assumed that the propagation effects may be neglected in concentrated grounding systems, such as vertical ground rods and shorter horizontal wires.

Often such classification, into concentrated or extended, is based on the physical dimensions of the grounding systems [1], but it should be based on the electrical dimensions. That means that the physical dimensions should be compared with the wavelength of the electromagnetic waves in soil. It is often required that the physical dimensions of the grounding systems are less than one tenth of the wavelength in soil [2] to neglect the propagation effects. Such wavelength should be determined for the largest frequency of interest in the transient study.
The largest frequency of interest in the transient study depends on the frequency content of the current and voltage impulses. It is a common mistake to estimate the largest frequency of interest only by the frequency content of the excitation current impulses [3]. However, it has been shown [4] that in such manner the largest frequency of interest for typical lightning current impulses may be underestimated to few hundred kHz, while the voltage impulse as a response to such excitation may have frequency content in a range of up to tens MHz.

On the other hand, the wavelength of the electromagnetic waves in soil also depends on the soil resistivity. Table 1 presents wavelength in soil for several values of frequency and soil conductivity and the maximal size of the buried electrodes for which propagation effects may be neglected [2].

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Conductivity (Ω·m)</th>
<th>Wavelength (m)</th>
<th>Electrode Size (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>10</td>
<td>707</td>
<td>70.7</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>2238</td>
<td>223.8</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>7076</td>
<td>707.6</td>
</tr>
<tr>
<td>500,000</td>
<td>10</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>31</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>98</td>
<td>9.8</td>
</tr>
<tr>
<td>1,000,000</td>
<td>10</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>22</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>66</td>
<td>6.6</td>
</tr>
</tbody>
</table>

Therefore, the classification of the grounding systems as concentrated or extended may by quite different in different soils and for different current impulses.

**Generation of high transient voltage peaks in grounding electrodes**

Figure 1(a) shows impedance to ground of 3-m vertical electrode in soil with resistivity 10 Ω·m and relative permittivity 10. Such electrode is usually classified as "concentrated" grounding, based on its physical dimensions, and consequently frequency independent. However it is obvious from Figure 1(a) that the impedance to ground is frequency dependent above about 200 kHz. Figure 1(b) show voltages between excitation point and ground for different excitation current impulses.

These are typical double-exponential impulses with different time to maximum and time to half maximum. When current impulse that have lower frequency content than 200 kHz is used as an excitation, the response does not include amplification in early time such as the voltage as response to current impulse with peak value 1 A with time to maximum 5 µs and time to peak half value 50 µs in Fig. 1(b).

However, impulses with shorter front times have higher frequency content and the voltages are amplified resulting in excessive transient voltage peak during the rise of the current impulse, such as impulses with 1 µs, 0.5 µs and 0.2 µs times to maximum, in Fig 1(b).

![Image of transient voltage to ground as response to current impulses with different times to maximum and times to half maximum.](image)

**Inductive and capacitive behaviour of grounding electrodes**

It can be seen in Fig. 1 that two frequency ranges may be distinguished: low frequency (LF) range, where the impedance is nearly constant, that is, frequency independent, and high frequency (HF) range, where impedance is changing with frequency. The limiting frequency is some character-
istic frequency $F_c$, [5]. Such characteristic frequency $F_c$ may be in the kHz range or up to MHz range, depending on the earth resistivity, electrode length and location of discharge point. The characteristic frequency $F_c$ is larger for smaller dimensions of the electrode and larger values of the earth resistivity and for central discharge point.

Figure 1 shows inductive behaviour where impedance is increased HF range. However, there is also a capacitive behaviour that is highly advantageous since the HF impedance is smaller than the LF resistance to ground. Such groundings will filter out HF from the response. Unfortunately, such capacitive behaviour is typical for electrodes with smaller dimensions and in highly resistive soil, and in nearly all other cases the grounding electrode behaviour is inductive.

Figure 3 gives the regions of inductive and capacitive behaviour of grounding electrode depending on the characteristic length and the soil resistivity. Here we define characteristic length of ground electrodes as the distance from the discharge point to the most distant point of the electrode. Figure 3 is approximately applicable for both horizontal and vertical electrodes.

Another difference between (1) and the formula in [5] is that here $\ell_c$ is a characteristic length. Fig. 4 illustrates (1). It is advantageous to use electrodes with characteristic length smaller than the critical length, $\ell < \ell_c$.

As a first approximation the characteristic frequency $F_c$ may be assumed as about 0.1 MHz for lightning first stroke and 1 MHz for return strokes [5].

Simple rules for better high frequency and transient behaviour of grounding arrangements

The grounding systems may be constructed of different elements, such as metallic elements of the structures buried in the soil or in the concrete of the foundations, and any supplemental grounding electrode, such as ground rods, horizontal rings, horizontal wires or any combination of these ground conductors. We define the characteristic dimension of the grounding system as the distance from a discharge point to the most distant point of the system.

The basic rule is to keep the characteristic dimension of the grounding systems as smaller as possible, constructing the system of as many short electrodes as needed for fulfilling resistance requirement. The first choice is to use electrodes small enough to have capacitive behaviour (Fig. 3). If this is not possible, then electrodes with inductive behaviour should be used providing that their characteristic length are smaller or as near as possible to their critical length (Eq. (1) or Fig. 5).

The application of these rules lead to the well-known rule that the grounding electrode arrangement should be always connected near its middle point and never at its edge point. Also in general, as many as possible paths for the current from and near the discharge point should be allowed.

All these rules may be in fact reduced to the following one rule: High frequency and transient performance is improved by minimizing the length and multiplication of the current paths from the discharge point to the ground through the grounding electrodes.

The application of these rules is illustrated in Fig. 4. Case A is end-driven and Case B is centre-driven 22-m copper wire with 1.4-cm diameter buried at 0.5-m. Case C are two parallel 18-m wires at 0.5-m distance, connected in the centre by 1.5-m wire. Case D is four-arm star with 6-m arm and 3-m rod in the centre. Soil is with $\rho = 200 \Omega \cdot m$ and $e_o = 10$. Injected current is $I_1/I_2 = 0.25/100 \mu s$.

If electrodes with inductive behaviour are used, then optimally characteristic frequency $F_c$ should be larger than the frequency content of the excitation current impulse. The characteristic frequency $F_c$ is larger for smaller dimensions of the electrode, larger values of the earth resistivity and for discharge point near the central point.

For every characteristic frequency $F_c$ there is a critical length $\ell_c$ above which HF impedance is larger than LF impedance [5]. The following formula, based on similar in [5], is deduced from the results of simulation [6]:

$$\ell_c = 0.6 \cdot (\sigma/F_c)^{0.41} \quad (1)$$

Figure 3: Regions of inductive and capacitive behaviour of grounding electrodes
return lightning impulse [6]. To obtain LF ground resistance \( R = 15 \Omega \), 22-m horizontal wire is used. However, the worst choice for the transient performance is to connect the wire at the end point (Fig. 4 Case A). Connection at the middle point (Fig. 4 Case B) improves significantly the transient voltages. Case C in Fig. 4 illustrates one possibility to allow additional paths for current. This also reduces the length between the feed point and the open end points of the conductors. Case D, where the length of the electrodes is smaller than the critical length \( \ell_c \) (1), removes transient voltage peak completely. However, better transient performance is achieved at a cost of larger total length of conductors, 37.5 m in Case C and 27 m in Case D compared to 22 m in Cases A and B.

![Figure 4: Improvement of the high frequency and transient performance of simple grounding electrode arrangements.](image)

**MODELLING OF COMPLEX AND EXTENDED GROUNDING SYSTEMS**

Another problem with modelling grounding systems is their possible extreme complexity. As an example we consider modelling of grounding system of high-voltage substations in urban areas where the ground potential rise (GPR) in case of ground fault [7] may cause dangerous voltages between telecommunication installations and local ground.

It is important to note that not only installations serving substations, but all other general use cables and telephone subscriber installations in the zone of influence are equally endangered and have to be protected [8]. The CCITT directives [9] define 430 V contour as a border of the zone of GPR influence on the telecommunication installation and all wire-line telephone subscriber installations inside such zone have to be protected [10].

If the high voltage substation is located out of urban area, the equipotential contours usually follow the form of the grounding system, tending to become circles at larger distances. Typically the ground potential value decays in radial direction from the zone of the substation, depending on the soil structure and resistivity.

However, if the high voltage substation is located in the urban area, its grounding system may be connected to a buried network of uncoated metallic sheathed cables. Although such cables are no longer manufactured in many countries, many of them are still in operation. Other buried metallic structures are also often located close to the substation grounding system and are extended throughout the urban area, such as metal sheaths of telecommunication and power cables, neutral wires of power distribution lines, water pipes, pipelines for
heating and gas, rails of traffic systems. If these buried metal structures are not taken into account, this may lead to underestimation of the zone of influence, as it is shown in [11]. Previous paper [12] has shown that metallic networks directly connected to the substation grounding system substantially affect the GPR zone of influence. However, all elements of the urban environment that affect potential distribution cannot be included in any model, firstly, because of the complexity of the problem, and, secondly, because there are numerous unknown elements of the urban environment. Presented results of measurements in [13] confirm this conclusion in a zone near the substation, while at a distance, especially in the highly urbanized zone, the additional buried networks of conductors tend to equalize potentials. The level of such equalizing of the potentials has to be determined experimentally [10]. This effect is included in the computer model by forcing the model to accept equalization of potentials in extent determined by measurements in a small number of points.

![Figure 6](image1.png)

Figure 6: Grounding system connected to cable network of existing 110/10 kV substation in urban area.

### Potential distribution around 110/10 kV substation in urban area

The computer software, described in the next sections, model is used for estimation of the GPR zone of influence around an existing 110/10 kV substation in case of a ground fault. The network of 10 kV buried uncoated metallic sheathed cables in a 2750 × 1750 m² area, illustrated in Fig. 6, is included in the model. The substation is in highly urbanized area that include complex underground network of water pipes, pipelines for heating, metallic sheathed cables for telecommunication and power, local grounding and other buried metallic structures. The influence of all these buried metallic structures is taken into account by forcing the model to accept measured potentials in a small number of points.

![Figure 7](image2.png)

Figure 7: Normalized values of calculated and measured values of the potential around 110/10 kV substation.

Figure 7 illustrates distribution of potential in a zone around existing 110/10 kV substation. Measured values are presented by impulses and simulated by surface.

### Protection of subscriber wire-line installations near high-voltage substations in urban areas

It may be concluded that the protection of the subscriber telecommunication installation based on the concept of the GPR zone of influence is not always applicable in the highly urbanized areas, where potentials may be equalized due to large underground networks of conductors. In such cases protection should be based on the potential difference between cable end points that may cause overvoltages in the telecommunication lines.

![Figure 8](image3.png)

Figure 8: Protection on the side of the subscriber and the exchange by gas discharge tubes.

In case when there is a potential difference between the subscriber local ground near the substation and the exchange local ground larger than 430 V, gas discharge tubes (GDTs) were used for protection, Fig. 8. To protect subscribers’ terminal equipment against overvoltages coming in by the telecommunication lines caused by GPR at high voltage substation, GDTs are connected between the line conductors and local earth [9]. The same is done on the side of the exchange.
SOFTWARE METHODS FOR ANALYSIS OF LOW AND HIGH FREQUENCY AND TRANSIENT BEHAVIOUR OF GROUNDING SYSTEMS WITH ARBITRARY GEOMETRY

Available software packages for analysis of transient performance of grounding systems are listed in [15]. Here, utilization of TRAGSYS [16], a software package for low and high frequency and transient analysis of grounding systems for Windows 95/2000/NT, is described.

![Figure 9: Actual computer screen appearance of the software for analysis of low and high frequency and transient behaviour of grounding systems.](image)

Calculation method

The software package TRAGSYS is aimed for computing the low and high frequency, and the transient behaviour of grounding structures. It uses an antenna theory model based on a rigorous integral formulation derived from the complete set of Maxwell’s equations. The solution is obtained in frequency-domain and the transient response by inverse Fourier transform techniques. Results are extensively validated by comparison with field measurements by the Electricité de France and by comparison with other authors’ models [17].

Basic assumptions of methods used are the following. Conductors are solid and straight, with horizontal or vertical orientation with circular cross section. They are bare and completely buried in soil, and are electrically characterized by conductivity. Conductor configuration may consist of arbitrary connected (and/or separated) networks of conductors. Soil is homogeneous and characterized by conductivity and permittivity. Conductor structure is energized by current injection in arbitrary number of points. The current is harmonic in frequency domain and is typical lightning (or user defined) impulse in time domain.

Data input and modification during interactive computer session

Input data consists of: geometrical data of a network of connected or separated buried conductors with arbitrary orientation, conductivity of the conductors and characteristics of soil, and location and shape of injected current impulses. User-friendly input of data is enabled in graphical mode, which enables easy definition and modification of the geometry after viewing the results.

Geometrical data may be entered during interactive computer session in graphical mode:

- by entering conductors’ Cartesian coordinates in a spreadsheet-like input data processor in a separate window using keyboard; and
- by simply drawing on the computer screen with a mouse.

Using mouse and close range zooming generally makes up drawing easy, but keyboard input of conductor’s end points’ coordinates is also enabled if maximum precision is required.

During all above actions the conductor network geometry is simultaneously displayed in the main graphical window. Additional 3D view of the grounding system is also enabled in a separate window, where rotation and zooming functions is easily enabled using mouse for better visualization. In all above methods of geometry definitions only end points of straight conductors are required. The program automatically determines all intersection and connection points and identifies nodes and segments in the conductor network.

Special tools are developed to make easy different drawing tasks, such as:

- automatic definitions of grids,
- automated definition of vertical conductors at selected points,
- automatic or manual definition of subdivisions of segments required for the numerical solution,
- aligning and bounding conductors together and connecting conductors to nodes.

Other common input data are entered in suitable menus. All data that are specific for one conductor
may be entered in a menu that contain all characteristics assigned to the selected conductor.

Geometrical data may be modified by several methods. Data may be modified using keyboard in the spreadsheet-like input data processor that enables access to all input data. Also, data for selected conductor may be modified by keyboard in the menu that contains its characteristics. Finally, geometry may be modified using mouse and drag and drop functions. Basic operation or manipulation of conductor segments is their selection. One or more conductor segments are selected with click of the left mouse button. Right mouse button invokes menu with conductor characteristics. Selected conductors then may be moved or deleted using mouse.

Representation of output results

Results of the computations are: impedance to ground, scalar potentials and/or electromagnetic fields, voltages along paths, leakage currents, all in frequency- and/or time-domain.

Output results are given as 2D plots and/or 3D perspectives. These results can be exported in EPS (Encapsulated PostScript) file format, as an ASCII text data or copied as an image in Windows Clipboard. Animation is enabled for both 2D plots and 3D perspectives for results in both frequency and time domains. Also output results are given in an ASCII text report.

CONCLUSIONS

Two important issues in the modelling of grounding systems have been addressed in this paper. The first one: high frequency and transient behaviour, most often related to EMC and lightning protection, and the second one: complexity of grounding systems in many practical situations where different metallic structures are connected or near. As a solution to both problems suitable software methods are described.

Considering the first issue: modelling of high frequency and transient behaviour of grounding systems the following is concluded:

- In cases of fast fronted current impulses, frequency dependent effects become dominant in the early time resulting in excessive peaks of transient voltages.

- When grounding systems are simple, such as vertical rod or horizontal wire, design procedures for reduction of such voltage peaks may follow simple rules. One such rule is to keep the characteristic dimension of the grounding systems (the distance from a discharge point to the most distant point of the system) as smaller as possible, constructing the system of as many “short” electrodes as needed for fulfilling resistance requirement.

- When grounding system is complex, then different scenarios may be tried looking for an optimal solution using suitable computer software.

Considering the second issue: modelling of complex grounding systems, an example of very complex grounding system of high-voltage substation connected to large network of burred metallic structures in urban area is analysed from the aspect of protection of subscriber wire-line installations against ground potential rise in case of power system fault. The following conclusions have been drawn:

- Grounding systems in urban area are highly influenced by different connected or near metallic structures, such as: complex underground network of water pipes, pipelines for heating, metallic sheathed cables for telecommunication and power, local grounding and other buried metallic structures. These metallic structures have large influence on the potential distribution around the substation. In such cases, the protection measures may be defined by direct evaluation of the potential differences that may cause overvoltages in the telecommunication lines.

- As a first step in the analysis potential distribution may be estimated by a computer model of the substation grounding system and all connected metallic structures. The effect of the other not readily known buried metallic networks, typical for urban environment, is included in the model based on measured potentials in a small number of specified points.

One solution is use of software methods that enable optimisation of grounding systems in an interactive computer session. Underlying computer programs are based on rigorous mathematical models and are verified by comparison with field experiments. Friendly user interface enable interactive easy definition and modification of the
grounding systems shape by drawing on computer screen with mouse utilizing drag and drop functions.

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REFERENCES


