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# GROUNDING SYSTEM TESTING USING A LOW-VOLTAGE U-I METHOD – SOME PRACTICAL ISSUES

# TESTIRANJE OZEMLJITVE Z UPORABO NIZKONAPETOSTNE U-I METODE – PRAKTIČNA VPRAŠANJA

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## Abstract

This paper deals with practical details of grounding system testing procedures in high-voltage substations. First, the low voltage U-I test method and the relevant legislation are presented. Next, the problems with practical implementation of the method and interpretation of the legislative are extensively described. At the end, the critical overview of the presented method considering possible influence on the decision-making process is given.

## Povzetek

Članek predstavlja praktične podrobnosti sistema testiranja ozemljitve v visokonapetostnih podpostajah. Na začetku je predstavljena nizkonapetostna U-I testna metoda in pripadajoča zakonodaja. V nadaljevanju je podrobno opisana problematika praktične implementacije metode in interpretacije zakonodaje. V zaključku je podan kritičen pregled predstavljene metode z ozirom na možne vplive na postopek sprejemanja končne odločitve.

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# 1 INTRODUCTION

The main challenge in modern power systems is to supply sufficient electricity at any place and at any time needed. Behind this lies a complex power system that has to fulfil that task. In parallel with increasing electricity demand, the power system is developed and over time requires an increasing amount of knowledge and effort spent in proper development and maintenance.

The grounding system is one of the main components of the electric power system and is essential for its safe and reliable operation. Therefore, particular attention is given to its maintenance. Legislation (regulations and recommendations) are the basic guidelines for which maintenance is performed properly, and it is necessary to have correct and complete regulations for maintenance.

The paper presents some implementation problems of the ordinance on technical requirements for power system substations with nominal AC voltage above 1 kV on measuring voltage conditions in high voltage substations. Maintaining the grounding is especially indicated as an integral part of substation maintenance process, and a critical review of the measurement results obtained in accordance with these regulations is presented.

# 2 GROUNDING IN HIGH-VOLTAGE SUBSTATIONS

## 2.1 Grounding definitions

Grounding is defined as the totality of all equipment and measures for grounding, while “to ground” means to connect electrically conductive parts with the earth through the grounding system, *[1]*, which is an important part of every power system. Three basic types of grounding are defined:

- Protective grounding

Grounding conductive parts that are not active parts, in order to protect people from electrical shock. Protective grounding means that electrically connected conductive metal parts are connected to the ground. It needs to ensure carrying away of unwanted currents (as a result of a malfunction in the electrical system, the failure on the consumer side, static charge, signal interference, switching surge, etc.), with the shortest and fastest route to the ground.

- Operational grounding

The grounding point of the active circuit, which is necessary for the proper operation of equipment and facilities. This implies a transformer or generator star-point grounding, directly or indirectly in order to achieve the desired network configuration.

- Lightning grounding

Grounding for carrying away lightning current into the ground requires a safe way for removing unwanted charges and currents that result from atmospheric discharges (lightning).

In this paper, only the high voltage (HV) electrical power stations are considered, so it is important to emphasize that different types of grounding in these facilities are not used separately but for all purposes is used one combined, grounding system.

## 2.2 The design of grounding in HV substations

Grounding systems are metal parts buried into the ground in order to establish a galvanic connection of the grounded part to the ground, *[2]*. Grounding is part of the overall grounding system that is directly deposited into the soil, *[3]*. The basic requirement for grounding is that its cross-section is big enough so it could take away high fault current in a short time. The material of which grounding is built must have good electrical conductivity and must not corrode under the conditions that are present in the soil. The most commonly used materials are copper and galvanized iron strips, primarily because of their good conductivity and corrosion resistance. Aluminium is sometimes used for parts of grounding systems that are above ground, but the regulations in most states prohibit such material for grounding because of the possibility of accelerated corrosion. The oxide layer formed as a corrosion product is not conductive, so it can reduce the effectiveness of the grounding. Grounding can be made in various shapes such as vertical rods, plates or horizontal mesh grounding. In HV stations, mesh grounding is used that is of the same order of magnitude as power station where it is placed, *[4]*.

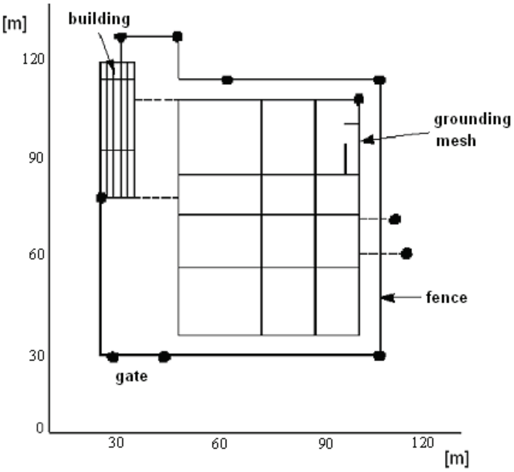

***Figure 1:*** *The principal scheme of the grounding mesh in relation to the substation fence*

Figure 1 shows the position of the grounding mesh in relation to the substation fence. In order to present the order of magnitude of the substation (100 × 100 m and more), the grounding scheme was put into a coordinate system with pointed axes in meters. Particular attention needs to be paid to the choice of materials of which the grounding will be made. Because of the above-mentioned properties, the most common choice for building the grounding mesh is galvanized iron bar, while copper cable has been used in recent years. When designing the grounding, certain requirements should be met. The designer must project the grounding to meet all the requirements in an optimal way (the technical achievement of objectives at minimum cost).

Therefore, to achieve optimal costs it must be buried at the optimal depth, which means the following:

a) It must be buried deep enough to avoid the influence of atmospheric conditions on the ground surface. This provides an optimum conductivity of the surrounding ground during the whole year. If it would not be fulfilled it could happen that the soil freezes as a result of cold temperatures, reducing its conductivity and thus directly increasing the propagation resistance of grounding. The same effect occurs when reducing or increasing the humidity of the soil.

b) It must be buried deep enough to achieve the optimum potential of the soil over the grounding. By increasing the depth of burial, the potential of the soil surface above the grounding decreases. Metal parts in the substation are connected to the grounding, which means that they achieve its voltage potential. After increasing the depth of burial, the soil surface potential decreases and the potential difference between ground and the metal masses is increasing. This increases the touch potential. The latter problem is particularly emphasized in substation fences where humans being are directly exposed to the touch potential. This is solved by forming potential around a fence.

In order to satisfy all these demands, it is experientially concluded that the optimum depth of grounding burial is at about 0.8 m.

## 2.3 Important parameters for the assessment of grounding system validity

The consequences of increasing the soil potential are touch and step potentials, and the potentials transferred through a cable bushing towards the next substations, *[5]*.

Step potential is a part of the grounding potential, due to the ground fault, that can be bridged by a step of 1-m length, assuming that current is flowing through the human body from one foot to another. When a person stays with both feet on different potentials, the difference of potential is the step potential where current flows from one foot to another. This voltage depends on the gradient of the potential along the distance from the grounding. If the potential gradient is higher, the person will bridge a larger potential difference.

Touch potential is a part of the grounding potential, due to the ground fault, which can be bridged with the assumption that the current is flowing through the human body from hands to feet (horizontal distance from the accessible portion is 1 m). In that case, the human is at such a distance from that the grounded metal surfaces can be reached; the two points that are at different potentials are bridged. One is a grounded metal mass that is at the potential of grounding, while the other is soil that is at a lower potential. This potential difference is the touch potential. It depends on the potential gradient in a way that the decrease of potential with distance from the grounding touch potential increases. However, when moving away from the grounding, it is no longer meaningful to talk about the touch potential because then the metal surfaces are out of reach. If, after installing the main (mesh) grounding, sufficiently low touch potential is not achieved (according to the regulations), additional grounding for forming the potential is needed as described above.

In order to keep the touch voltage and the step voltage in permitted levels, the suitable arrangement of grounding systems and potential forming is used, *[6]*.

Transferring the potential from substations through the buried metal installations in remote areas remains a problem that arises in the case of earth faults. Due to the flow of current from the grounding network to the ground, the potential of the ground is rising. Equipotential lines (lines of the same potential) follow a form of grounding in its vicinity, while with increasing distance tend to assume the shape of a sphere. If other metal objects are present near the grounding network or attached to it, there is a distortion of equipotential lines. This means that the potential near a metal object is no longer declining in the funnel shape of the potential around the grounding system, but decreases more slowly or keeps a constant value. One such example is shown in Figure 2.

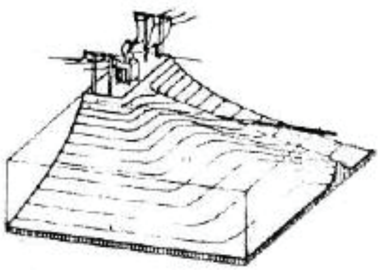

***Figure 2:*** *Potential funnel in the direction of cable exit*

The figure clearly shows the funnel-shaped potentials around the substation and equipotential lines. However, around the cable bushings comes the distortion of equipotential lines in terms of the slower decline of potential which can lead to transmission of this potential in remote areas and in adjacent substations. That would not be expected if the potential would be falling into the funnel shape around the entire substation.

The dangerous consequences of transferring the potentials are:

a) the risk of touch potential for the people who come into contact with the transferred potential,
b) thermal overload of metal cable shield due to increased currents,
c) electrical insulation overexertion.

## 2.4 Testing method

Reliable and correct operation and safety of personnel and equipment are the basic requirements of the existing technical regulations on substations in the case of earth faults. Theoretical considerations and calculations are not enough to predict and describe all phenomena on grounding in fault conditions. Therefore, after the construction of the substation, as well as periodically during its operation, the measurements on grounding are performed. After construction, the measurements are performed to examine the validity of the project and performance of grounding in order to physically verify the designed parameters. During the exploitation, measurements are performed periodically to determine the changes in grounding. Measurement of voltage conditions is performed using a low-voltage (U-I) method, which involves measuring the potential of the grounding and the transferred potential, equipotential lines recording and measurement of touch and step potentials. The principle of the low-voltage measurement method lies in the fact that the application of AC voltage, whose frequency is approximately equal to the frequency of the system, between the grounding system and distant grounding, results in the current *I*. Hence, the measurable potential occurs on the grounding. The measured values of the potential and touch and step voltages are then proportionally recalculated to the maximum current that can flow through the grounding of the object due to the primary single-pole short circuit.

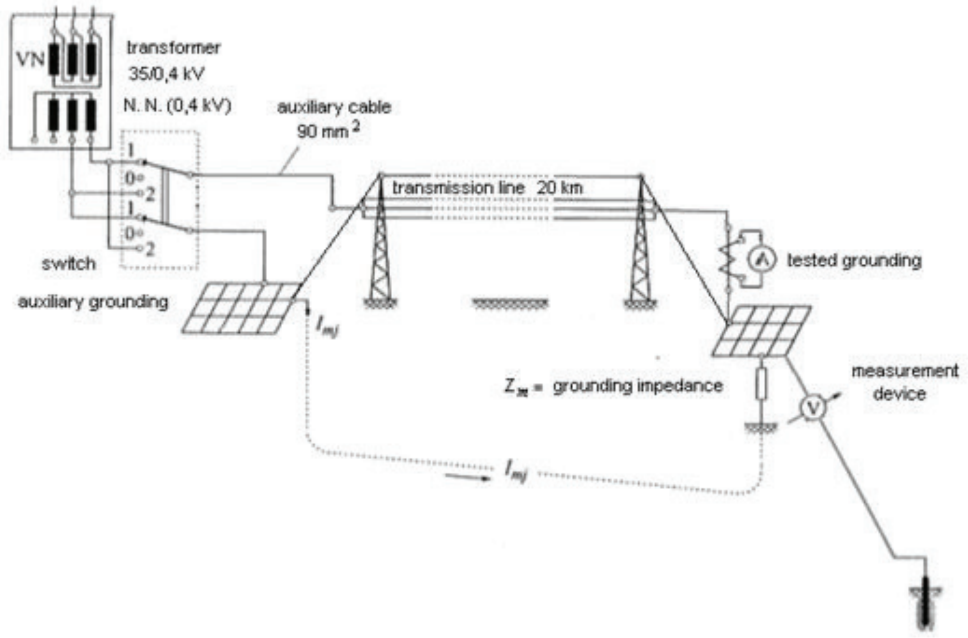

***Figure 1:** The principal scheme of grounding measurements using U-I method*

The results obtained and recalculated to the highest single-pole short-circuit current represent voltage conditions on grounding that would appear in case of single-pole earth faults in the substation or on the transmission line and serve as a basis for further decisions on the condition of the substation and possible corrective action to the grounding, *[7]*.

## 3 THE APPLICATION OF EXISTING LEGISLATION ON GROUNDING SYSTEM MAINTENANCE IN HV STATIONS

In November 2010, “Ordinance on technical requirements for power system substations with nominal AC voltage above 1 kV” (NN 105/2010)[8] became valid, replacing “Regulations on technical standards for power system substations with nominal voltage above 1000 V” (Official Gazette of SFRY, no. 4 / 74 and 13/78, article 53 of the Law on Standardization -"Official Gazette no. 55/96 and Article 39, paragraph 1 of the Law on Technical Requirements for Products and Conformity Assessment - Official Gazette, no. 20 / 10) [9]. In accordance with amendments to the legislation, the method of measurement is adjusted. The new regulation regarding the voltage conditions on the grounding refers to International standard EN 50522 accepted as Croatian Standard HRN EN 50522:2010, *[1]*. With this act, the recommendations contained in the Croatian standard become obligatory.

Furthermore, some of the details and problems of application of the legislation on maintenance of grounding are described, as well as suggestions for improving future versions of the legislation.

## 3.1 Details of applying legislation in terms of maintaining the grounding in HV substations

Measurements of voltage conditions on grounding in high-voltage substations are performed, aiming to define the statement about the acceptability of voltage conditions at the moment of the ground fault, i.e. about the safety of people and property at the substation and its vicinity. In the case of death of people and property damage, the question of responsibility could be stated. Furthermore, the question of to what level of detail the legislation defines the procedure for testing the grounding and determining the key parameters for safety raises. Therefore, this section deals with the question of how much freedom the legislation leaves to measurement procedure and what consequences it can have on the final statement about the acceptability of voltage conditions.

The valid standard for grounding in HV substations recommends the U-I method, following simple guidelines; however, that is all written based on a principled understanding of the method. Details of the implementation of a measurement procedure are the result of logical reasoning and assumptions of the measurer, so in the case of an investigation of the possible occurrence of hazards at the station or its vicinity, despite the acceptable measurement results, measurements could become unreliable.

Furthermore, the more details that are not completely regulated by law are considered. Finally, possible consequences of incorrect assumptions on final decision considering acceptability of voltage conditions are assessed.

### 3.1.1 Time limits for testing grounding

Testing of the grounding is performed after the construction of substations within which is the grounding as well as periodically during normal operation. After applying the “new” regulations, time limits for testing voltage conditions at the grounding was reduced from 5 to 4 years (Article 71, paragraph 1). However, a misunderstanding arises, when reading Article 67 Paragraph 4, which states the following, *[8]*:

> (4) *Maintenance of substations that has been performed or is performing in accordance with regulations applicable earlier must be such that, during the substation lifetime, the technical characteristics of the substation are preserved and that they meet the requirements of the building design regulations and are in accordance with which the substation is made.*

Does this mean that the new regulations do not apply to existing substations rather than the maintenance of such facilities are carried out in accordance with the old regulations?

### 3.1.2 The impact of weather conditions

Weather conditions can have a significant impact on the measurement results, especially on touch and step potentials. It is clear that changes in humidity and specific soil resistance change test results, however, the question is how great this change is *[10, 11]*. If the change is small compared to the measurement results, the measurement could be performed under any weather conditions (dry soil, moist soil, etc.). However, what if this change is not negligible? The law does not define the impact of weather conditions on the measurement results and therefore does not determine or recommend the conditions under which the measurement must be or should be performed.

### 3.1.3 The influence of the measurement equipment

The impact of measurement equipment is also not negligible. The law does not prescribe which way current is to be injected into the electrical measuring circuit. This is done using a substation distribution transformer that connects via cable to a transmission line. The test current is 50-100 A. For this current cable with copper conductor cross section 16 $mm^2$ would be sufficient. With long-term measurement cable heating could be caused, so test current would be reduced. This would result in different test currents during a single measurement. That would hinder the process of recalculation of measured results on the actual short-circuits. It is obvious that it is necessary here to use a larger cable cross-section (e.g. 90 $mm^2$). The question is how much changing the test current is allowed during the measurement. The law does not prescribe anything about that so the question remains open.

### 3.1.4 The amount of test current and duration of measurement

In relation to the preceding paragraph, the question is raised about the amount of test current and duration of the measurements. Croatian standards state that test current shall be such that the measured values (potential of grounding, touch, and step potentials) at the test current must be greater than the disturbance voltage. However, how much greater is not stated. It is stated only that it is generally achieved with a test current of 50 A. The question is how to achieve that current. Measures to achieve a sufficient amount of test current are not defined in the regulations. It is not advisable to use excessive current that can dry out the soil over long-term measurements. The question is how long the optimal duration of the measurements is and what the optimal test current is.

### 3.1.5 Location of test current injection in tested grounding

When closing the current measuring circuit, it is necessary to specify the location of the injection of test current in tested grounding. The question is on which location is it allowed to do so. The law does not prescribe anything about it, so it can be concluded that it is possible anywhere, e.g. on a substation fence. The most commonly chosen location is where a short circuit can realistically occur. Once the connection to the arbitrarily chosen point is set, the question arises of whether at that point good connection with a grounding in the soil is made. If not, the results of measurements could be completely wrong. The logical solution is to inject current in many places, but that would extend the duration of the measurements. Whether to measure in several locations and how the law does not specify, so the question remains open.

### 3.1.6 Measuring the potential of the grounding

The grounding potential is measured between the grounding and distance soil. The question that arises here is when an area can be called distant soil and how far is that and how to determine it. An order of magnitude of distance and how it is determined, however, have no legal basis but is determined based on years of experience. The material from which the probe is made is also not determined. Chemical reactions of the soil and the probe could lead to the creation of additional potential, which would undermine the results of measured potential.

### 3.1.7 Reduction factor of protection rope

For the calculation of current through the grounding, which is relevant for further calculation, a reduction factor of the protection rope is considered. The question is how to determine the exact reduction factor. The Croatian standard recommends a method for calculating on the basis of self-impedance of phase conductor and protection rope. The self-impedance of the phase line depends mostly on the average distance between the phase conductors and protection rope from which it is obvious that the calculation of the reduction factors will not give exact but only approximate values. The procedure for measuring the reduction factors are not determined or recommended. Therefore, the influence of protective rope is taken into account only approximately and the exact impact, because of ignorance of the exact reduction factors, remains unclear.

### 3.1.8 Drawing a grid for recording equipotential lines

When generating ancillary measure documentation for the purpose of recording the equipotential lines, it is necessary to make a grid over the area around the substation in order to locate the points for measuring the potential. The question is how much that grid must be dense or how many measuring points should be placed on the substation surface. Therefore, the optimal number of measuring points and the way they are distributed throughout the substation are not determined or recommended, so it remains the arbitrary decision of the measurer. Is it even necessary to measure the potential and record equipotential lines and whether there would be other ways to determine dangerous touch and step potentials? The legislation says nothing on this, so these questions remain open.

### 3.1.9 Determination of measurement points to measure touch and step voltage

After determining equipotential lines, it is necessary to locate points of abrupt change in potential and to identify those points as possible sites of dangerous touch and step potentials. The question that arises is at which point sudden changes in potential is enough so that they can represent a possibly dangerous place. Furthermore, it is unclear whether it is permissible to measure touch and step potentials in the places of the maximum potential gradient, and if they are within acceptable limits to conclude that touch and step potentials at other locations in the substations and outside it are within the allowable limits. The question is what precision is needed in the gradient analysis. The precision of gradient analysis increases proportionally to the number of points where the potential is measured. The Croatian standard does not state anything about choosing locations for performing measurements of touch and step potentials.

### 3.1.10 Transferring the potential to the surrounding objects

As a part of high voltage grounding testing, the transferred potential in the surrounding objects is also measured. Regulations applicable to low-voltage systems prescribe the dependence curve of touch potential in low voltage systems on the total switch-off time in case there is a risk of the transferred potential, but does not define the allowed amount of grounding potential in that substation. Croatian standards do not prescribe the exact values of permitted transferred potential. In many publications, the allowed amount of the transferred potential in the buildings are up to 50 V; however, there is no firm foundation for that amount.

### 3.1.11 Interpretation of Regulations

The terms of the ordinance are left to the subjective interpretation of the reader, and it is, therefore, necessary, in order to use it correctly, to appoint a person or institution to be responsible for their interpretation.

## 4 CONCLUSION

After a review of the details of the measurements procedure, the conclusion is that the measurer has great freedom and the ability to influence the results. A number of these influences and subjective decisions can significantly alter the results of measurements. Thus, the question is what if one would have to ensure the reproducibility of the measurement results, i.e. if the significant precision has to be achieved (closeness of results of repeated measurements) but with changes of influential factors (measurer, measuring equipment, weather, time interval). Comparing the two different measurers and their measurement procedures, all the details of the measurement procedure that are left to subjective decision-making (not prescribed by legislation) could be different. It is highly possible that the results of measurements are different. Hence, the question is which measurement procedure is correct and whether the results of these measurements are credible at all.

The following point becomes very serious because the results are the basis for deciding on the admissibility of voltage conditions under which commissioning of substations will be granted. In the case of misinterpretation of test results and endangering people and property, all the freedom that the legislation has allowed to the measurer becomes a disadvantage because a subjective decision, i.e. one without legal basis, cannot provide a firm foundation to confirm the credibility of measurement results.

It is necessary to direct a significant amount of knowledge and resources in scientific and technical research in this area in order to resolve at least some of the above-mentioned problems. Implementation of these solutions in the legislation is essential to achieve significant progress in terms of the reliability of power systems and, most importantly, in terms of safety of people and property.

## References

[1] **‘Earthing of power installations exceeding 1 kV a.c. (EN 50522:2010)**’, 2012

[2] **F. Majdandžić:** *Uzemljivači i sustavi uzemljenja*, Graphis, 2004

[3] **J. Nahman, I. Paunovic:** *Mesh voltages at earthing grids buried in multi-layer soil*, *Electr. Power Syst. Res.*, 2010, vol. 80, iss. 5, pp. 556–561

[4] **I. Tolić:** *Determination of voltage conditions on the protection grounding of high voltage substations*, M.sc. Thesis, 2008

[5] ‘**Power Installations Exceeding 1 kV a.c.** (HD 637 S1:1999)’, 2002

[6] **S. Nikolovski, D. Čavlović, P. Marić, Z. Baus:** *Computer Aided Design of Power Plant Grounding System*, in ‘26th Scientific Conference Science to Practice’, 2008

[7] **D. Navečerel:** *Development of the model for calculation of earthing zero- sequence currents in high voltage substations*, in ‘HRO Cigre’, 2001, pp. 43–52

[8] **‘Pravilnik o tehničkim zahtjevima za elektroenergetska postrojenja nazivnog izmjeničnog napona iznad 1 kV (NN 105/2010)’,** 2005

[9] **‘Pravilnik o tehničkim normativima za elektroenergetska postrojenja nazivnog napona iznad 1000 V (SL. 4/74)’,** 1974

[10] **H. Markiewicz, A. Klajn:** *Earthing Systems - Fundamentals of Calculation and Design*, Wroclav University of Technology, 2003

[11] **T. Barić, D. Šljivac, M. Stojkov:** *Validity Limits of the Expression for Measuring soil resistivity by the Wenner method according to IEEE Standard 81-1983*, *Energija*, 2007, vol. 56, iss. 6, pp. 730–753