The ground potential rise (GPR) in high voltage substations in case of ground faults 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. The CCITT directives define 430 V (or 650 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.

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, with decaying values 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. Other buried metallic structures are also often located close to the substation grounding system and are extended through out 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 it may lead to underestimate of the zone of influence.

Although national and international regulations define the potential contour 430 V (650 V) as a border of the GPR zone of influence on telecommunication installations in case of faults to ground inside a high voltage substation or on a connected power line, if the substation is in highly urbanized area, the potentials are equalized due to large and complex underground metallic networks. In such cases, as more suitable to define the protection measures are potential differences that may cause overvoltages in the telecommunication lines.

A computer model of the substation grounding system that include connected and near metallic structures is developed. As an example of its capabilities, network of 10 kV buried uncoated metallic sheathed cables in a 2750 × 1750 m² area, illustrated in Fig. 1, is included in the model. The computer model is validated by comparison with other author’s software and with direct comparison with field measurements, Fig. 2.

This model is used to estimate the GPR zone of influence to the consumer installations in urban environment. The effect of the equalizing of potentials by other buried metallic networks that are typical for urban environment and are usually unknown is included in the model as a correction based on measured potentials in a small number of specified points.
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This model is used to estimate the GPR zone of influence to the consumer installations in urban environment. The effect of the equalizing of potentials by other buried metallic networks that are typical for urban environment and are usually unknown is included in the model as a correction based on measured potentials in a small number of specified points.
INTRODUCTION

The ground potential rise (GPR) in high voltage substations in case of ground faults [1] 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 [2,3,4]. The CCITT directives [5] 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 [6].

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 [7].

However, if the high voltage substation is located in the urban area, its grounding system is often connected to a buried network of uncoated metallic sheathed cables [8]. 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 [9], this may lead to underestimation of the zone of influence, as it is shown in [10]. Previous papers [11,12,13] have 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.

This paper presents results of measurements that 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 [6,14]. This effect is included in the computer model by forcing the model to accept equalizing of potentials in extent determined by measurements in a small number of points.

MODEL OF THE GROUNDING SYSTEM CONNECTED TO UNDERGROUND CABLE NETWORK

The model of a substation grounding system connected to underground cable network is illustrated in Fig. 1. It is based on the following assumptions [8,11,17,]. The grounding electrodes are modeled as a set of connected conductors buried in homogeneous or two-layer soil. The uncoated metallic cable sheaths are directly connected to the grounding conductors and are connected to 10/0.4 kV local substations or to other cables.

The grounding electrodes are divided into \( n_g \) segments, and the cables are divided in \( n_c \) segments. Cables are considered to have
longitudinal impedance, with equivalent circuit illustrated in Fig. 2 [8,17]. The parameters $y_k$ denote the longitudinal admittance of cable $k$ sheath segment, $i_k$ denotes the current emanating to the soil from sheath segment $k$, while $I_k$ denotes current flowing through sheath segment $k$. The potential of the source substation is $u_g$, while $u_k$ is the potential of the sheath segment $k$. The consumer substation grounding system is denoted by the admittance $y_{kt}$. The parameters needed for the circuit in Fig. 2 are obtained using measured data for given types of cables [11].

For this model of a cable, the following relation can be written

$$-i_k = Y_{ph} \cdot i_u + Y_k \cdot u_k,$$  \hspace{1cm} (1) 

where

$$Y_{ph} = \begin{bmatrix} y_0 & 0 & \cdots & 0 \\ 0 & y_0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & y_k \end{bmatrix},$$  \hspace{1cm} (2) 

$$Y_k = \begin{bmatrix} 0 & -y_k & 2y_k & \cdots & \cdots & 0 \\ -y_k & 0 & -y_k & \cdots & \cdots & 0 \\ \vdots & \vdots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \vdots & \cdots & 0 & -y_k & y_k \end{bmatrix}.$$  \hspace{1cm} (3) 

Equation (1) is valid for all cables emanating from the source substation if the specific values for parameter $y_k$ and $y_u$ are used. Consequently, based upon (1), the following general equation, including all radial positioned cables, can be written

$$-i_c = Y_g \cdot i_u + Y_c \cdot u_c,$$  \hspace{1cm} (4) 

where

$$i_c = \begin{bmatrix} i_1 \\ i_2 \\ \vdots \\ i_n \\ \vdots \\ i_m \end{bmatrix}, \, i_u = \begin{bmatrix} i_{u1} \\ i_{u2} \\ \vdots \\ i_{um} \end{bmatrix}, \, u_c = \begin{bmatrix} u_{c1} \\ u_{c2} \\ \vdots \\ u_{cm} \end{bmatrix}, \, u_g = \begin{bmatrix} u_{g1} \\ u_{g2} \\ \vdots \\ u_{gm} \end{bmatrix},$$  \hspace{1cm} (5) 

$$Y_g = \begin{bmatrix} y_{g1} & y_{g2} & \cdots & y_{gn} \\ y_{g2} & y_{g1} & \cdots & y_{gn} \\ \vdots & \vdots & \ddots & \vdots \\ y_{gn} & y_{g2} & \cdots & y_{g1} \end{bmatrix}, \, Y_c = \begin{bmatrix} Y_{c1} & \cdots & Y_{cn} \\ \vdots & \ddots & \vdots \\ Y_{cn} & \cdots & Y_{cc} \end{bmatrix} \text{diag} \{Y_c\}.$$  \hspace{1cm} (6) 

In case of complex cable configuration, the matrix $Y_c$ is not diagonal, and it takes the form, which corresponds to mutual cable connections.

The previous equations imply that there is no mutual magnetic coupling between cable segments. Such an assumption holds practically for the uncoated, steel armored lead sheathed three-phase cables that are commonly used in distribution systems. For unarmored cable constructions with uncoated metal sheaths the expressions (6) are approximate.

Voltages $u_c$ depend on the currents flowing from cable sheath segments and from the source substation ground electrode into the soil. This relationship can be expressed as

$$u_c = R_{ph} \cdot i_u + R_{gc} \cdot i_c,$$  \hspace{1cm} (7) 

The analogous equation for the source substation ground electrode will be

$$1_y \cdot u_u = R_{ph} \cdot i_u + R_{ph} \cdot i_c.$$  \hspace{1cm} (8) 

From the current continuity law it follows

$$1_y \cdot u_u + 1_y \cdot i_c = 0$$  \hspace{1cm} (9) 

If we substitute $u_c$ from (7) into (4), the following relationship is obtained

$$Y_c \cdot R_{ph} \cdot i_u + (Y_c \cdot R_{gc} + E) \cdot i_c + Y_g \cdot u_u = 0.$$  \hspace{1cm} (10) 

Relations (8)-(10) build a closed system of linear equations that can be solved for $i_p$, $i_c$, and $u_g$.

VALIDATION OF THE COMPUTER MODEL

The validation of the results of computer analysis is based on the comparison with field measurements performed by the Electricite de France, Paris, France, in the period 1976-85. An extensive set of experiments had been performed for different grounding electrodes arrangements [15]. Some comparisons for low and high frequencies are documented in [16].

Figure 3 shows comparison with measurements in case of irregular and complex arrangement of ground electrodes [18], and Fig. 4 direct comparison in urban area is presented for the practical case given in in the next part.

The computer model was also compared for power frequencies with other authors' software [19], with excellent agreement of the results, Fig. 5. Results in Fig. 5 are magnitudes of the electric field component along profile A-A at earth's surface for the illustrated ground grid. Conductors are constructed...
of copper with radius 0.5 cm, and grid is buried in soil with $\rho = 100 \, \Omega \cdot \text{m}$ at 0.5 m depth. Current of 1 kA at power frequency is injected at the central point.

**POTENTIAL DISTRIBUTION AROUND 110/10 kV SUBSTATION IN URBAN AREAS**

The computer 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 $2750 \times 1750 \, \text{m}^2$ area, illustrated in Fig. 6, is included in the model. The substation's surrounding is a highly urbanized area, on the right side in Fig. 5, and partially urbanized area, on the left side in Fig. 5. For the same case detailed measurements were made. The measurements were done using current injection method, following procedures in [14].

![Comparison with field measurements](image1)

**Figure 3:** Comparison with field measurements.

![Normalized values of calculated and measured values of the potential along a profile near 110/10 kV substation](image2)

**Figure 4:** Normalized values of calculated and measured values of the potential along a profile near 110/10 kV substation.

![Comparison with other authors’ model](image3)

**Figure 5:** Comparison with other authors’ model.

![Grounding system connected to cable network of existing 110/10 kV substation in urban area](image4)

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

![Measured values of the voltage between grounding system and local ground using current of 100 A](image5)

**Figure 7:** Measured values of the voltage between grounding system and local ground using current of 100 A.

Results of the measurements using simulated ground fault current of 100 A are given in Fig. 7. Two areas could be separated in radial distance around the substation. On the right side in Fig. 7,
the 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, produces equalizing of the potential at a distance of the substation. Such effect is not visible on the left side in Fig. 7 for partially urban area. This result is in accordance with similar already reported in [6,14,20].

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 that may cause overvoltages in the telecommunication lines.

PROTECTION OF SUBSCRIBERS’ AND EXCHANGE INSTALLATIONS

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 [5]. The same is done on the side of the exchange.

CONCLUSION

When the grounding system of a high voltage substation is connected to uncoated metallic shielded cables, they act as a part of the grounding system, and have large influence on the potential distribution around the substation. National and international regulations define the potential contour 430 V as a border of the GPR zone of influence on telecommunication installations in case of faults to ground inside a high voltage substation or on a connected power line. However, if the substation is in highly urbanized area, the potential is equalized due to large and complex underground metallic networks. In such cases, as more suitable to define the protection measures are potential differences that may cause overvoltages in the telecommunication lines.

A computer model of the substation grounding system and all connected uncoated metallic sheathed cables is developed. This model is used to estimate the GPR zone of influence to the consumer installations in urban environment. The effect of the equalizing of potentials by other buried metallic networks, typical for urban environment, is included in the model based on measured potentials in a small number of specified points.

ACKNOWLEDGMENT

The work was partially supported by the Ministry of Science of Republic of Macedonia.

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