Earth Potential Rise Influence Near HV Substations in Rural Areas

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Introduction

Where high and low voltage earthing systems exist in proximity, part of the EPR (earth potential rise) from the HV system is impressed on the LV system. Two practices are presently used:

a) Interconnection of all HV with LV earthing systems.
b) Separation of HV from LV earthing systems.

In either case, the IEC Standard 61936 (Safety in HV installations above 1 kV) specifies that requirements concerning step, touch and transfer potentials shall be complied with within the substation and at LV installations supplied from that substation. In North America, MV lines are usually equipped with a MGN (multigrounded neutral) that connects the earthing systems of the HV substation, the LV installations and the telecommunication systems.

In some cases, particularly in rural areas, questions are raised concerning the transfer in LV installations of the EPR resulting from a fault in the HV substation. The concerns relate both to safety and the protection of telecommunication circuits entering the substation. This has led Hydro-Québec to initiate a project aimed at characterizing the transfer of the EPR from HV substations in rural areas.

![Figure 1: Location of Arthabaska substation and of measuring sites on the MV and LV system](image1)

![Figure 2: Description of the MV network](image2)
1. DESCRIPTION OF THE FIELD TESTS

Field tests were performed in a 120/25 kV substation, located in a rural area (see Figure 1), 4 km south of Victoriaville, a city of 40 000 inhabitants. A double circuit 120-kV line feeds the 100-MVA substation. The substation feeds six overhead 25-kV lines (see Figure 2). Lines L1 and L2 are fed via a 200-m long cable section. The cable section is 1.2-km long for lines L3 and L4 and 1.5-km for lines L5 and L6. The cable sheaths connect the substation earthing system to the MGN of the overhead lines. Soil resistivity measurements were performed in the substation area. Results were used to calculate the parameters of a two-layer soil structure model. The upper layer, 10-m deep, has a resistivity of 100 Ω⋅m; the lower layer has a resistivity of 6 Ω⋅m only.

Faults were staged at the 120-kV level using low amplitude currents (10 A) at frequencies close to 60 Hz. One 120-kV circuit was put out of service and used for the injection between Arthabaska and Kingssey substations, 24 km apart. GPS receivers were used to synchronize the measurements taken at remote locations.

Measurements at the substation include the current distribution in the earthing system, the EPR of the substation along a profile extending up to 1 km (Figure 1) and touch voltages between metallic structures and soil. Measurements were also performed at eleven sites along the MV system and in LV installations. They include the current in the MGN (neutral conductor and telecommunication cables) and the neutral-to-earth voltage measured at 1, 10 and 25 m from a local earth electrode (typically 3-m earth rods).

2. RESULTS

2.1 EPR and earth currents at the substation

Figure 3 shows the current distribution in the substation earthing system. The measured currents include the injected current (I_{inj.}) and those exiting the substation: the current in the skywire of the HV line (I_{hv}), in the sheaths of the MV cables (I_{transf.}) and in the neutral of the transformer feeding the substation load during the tests (I_{transf.}).

The latter results from the induced voltage on circuit 2 due to the current I_{inj.} circulating in circuit 1. During an actual fault, both circuits would contribute to the fault current and I_{transf.} would be zero. The actual EPR would therefore be 13% [I_{inj.}/(I_{inj.} - I_{transf.})] higher than measured during the tests.

The maximum value of the EPR at Arthabaska substation is caused by a single-phase fault at the 120-kV bus. The contribution of the 120-kV lines for that fault is less than 5 kA. The maximum EPR of the substation is therefore less than 565 V (5 000 A*0.1 V/A*1.13).

The current in the substation grid (I_{grid}) is deduced from the measured currents (I_{grid} = I_{inj.} - I_{hv} - I_{transf.} - I_{transf.}). The current in the skywire (I_{sky}) includes two components: the current in the earth impedance of the HV line (I_{hv}) and an induced current (I_{ind.}) that results from the magnetic coupling between the phase conductor carrying the injected current and the skywire. Using Carson’s equations, I_{ind.} is estimated using the 120-kV line parameters given in Figure 1 and assuming a homogeneous soil resistivity of 50 Ω⋅m (a calculation example is found in [1]). Soil resistivity varies along the line. However, the current in the earth impedance of the HV line (I_{hv}) varies only by ±12% for soil resistivity comprised between 5 and 500 Ω⋅m.

From the EPR and the current distribution in the substation earthing system, it is possible to determine the impedance of the substation earthing components (see Table 1). The impedance of the global earthing system of the substation is 0.12 Ω. The main contribution comes from the substation grid (0.18 Ω), which carries more than half of the current. The impedance of the MV network is half that of the HV line.

Table 1: Impedance of the earthing system components as seen from the substation

<table>
<thead>
<tr>
<th>Component</th>
<th>Impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substation grid</td>
<td>0.18∠8°</td>
</tr>
<tr>
<td>MV network</td>
<td>0.35∠71°</td>
</tr>
<tr>
<td>HV line</td>
<td>0.76∠7°</td>
</tr>
<tr>
<td>Global system</td>
<td>0.12∠25°</td>
</tr>
</tbody>
</table>

2.2 EPR and earth currents on the MV system

The current in the MGN and the neutral-to-earth voltage were measured at the cable to overhead transition of each of the six lines. Table 2 presents the results.

I_{MGN} is the total of the currents circulating in the neutral conductor and in the metallic sheaths of the telecommunication cable(s) (see Figure 2).

As seen in section 2.4, the voltage reduces sharply around earth electrodes due to the upper to lower layer soil resistivity ratio superior to 10. As a consequence, the mutual resistance between the earth electrodes on the MV line and between MV lines and the substation can be neglected. The neutral-to-earth voltages measured at 25 m from earth electrodes along the line can therefore be considered equal to the EPR. The impedance of the MGN (Z_{MGN} = EPR/I_{MGN}) can therefore be obtained from these measurements.
More than 30% of the substation EPR appears on the MGN at 1 km. Figure 5 shows the EPR on the MGN of lines L1 and L2. Figure 4: Current on the MGN along lines L1 and L2. Almost 70% of the current injected in L1 goes to earth within the first 1.5 km whilst this fraction is only 40% for L2. This is due to the fact that L2 feeds very few costumers over the first km (see Figure 1); the contribution of the earth electrodes from LV installations is therefore reduced. It also explains why the earth impedance of L2 is 20% higher than that of L1 (Table 2).

As it will be seen in section 2.3, higher soil resistivities contribute to increase both the EPR and the distances at which the voltages are transferred on MV and LV installations.

2.3 Influence of the soil resistivity on the EPR

The earth impedance and the propagation constant (distance for which the voltage reduces to $e^{-1}$ the value at $x=0$) of long lines increase as the square root of the soil resistivity [3]. Figure 6 gives an example. Measurements at the Arthabaska substation are compared to those performed on a rural line in Mont-Laurier [2] where the soil resistivity exceeds 1 000 $\Omega\cdot$m. The underground to overhead transition on lines L1 and L2 (site S5) is considered as the injection point. Although the soil resistivity is 10 times higher in Mont-Laurier, the impedance of the line is 3.5 times higher only (1.3 $\Omega$ compared to 0.37 $\Omega$ for lines L1 and L2 in parallel). Moreover, while the EPR drops to 37% ($e^{-1}$) of the value at $x=0$ in approximately 0.9 km on L1 and L2, 2.6 km are required on the Mont-Laurier line due to the higher soil resistivity. The MGN transfers the substation EPR over larger distances in higher soil resistivity areas.

The resistance of the substation grid increases linearly with soil resistivity. Since the impedance of lines increases only as the square root of the soil resistivity, the contribution of the MV network to the substation earthing system increases with soil resistivity.

2.4 Zone of influence of the substation

The soil in the vicinity of the substation assumes a fraction of the EPR. For the purpose of the protection of telecommunication circuits, the concept of zone of influence has been introduced [1, 4]. It is defined as the area around the substation where the potential at the surface of the soil exceeds a permissible limit (typically between 300 and 400 V). Figure 7 presents the earth potential measured along the profile shown in Figure 1. The potential drops to 20% of the EPR in less than 100 m. Since the soil in the upper layer is more resistive than in the lower layer, the potential drops rapidly.

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Table 2: Impedance of the multigrounded neutral at the underground to overhead transition

<table>
<thead>
<tr>
<th>line</th>
<th>$EPR/I_{ij}$ (V/A)</th>
<th>$IMGN/I_{ij}$</th>
<th>$Z_{MGN}$ ($\Omega$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>0.075∠3°</td>
<td>0.111∠-34°</td>
<td>0.68∠37°</td>
</tr>
<tr>
<td>L2</td>
<td>0.075∠6°</td>
<td>0.089∠-23°</td>
<td>0.84∠29°</td>
</tr>
<tr>
<td>L3</td>
<td>0.019∠-39°</td>
<td>0.026∠-72°</td>
<td>0.74∠33°</td>
</tr>
<tr>
<td>L4</td>
<td>0.019∠-39°</td>
<td>0.027∠-78°</td>
<td>0.70∠39°</td>
</tr>
<tr>
<td>L5</td>
<td>0.013∠-58°</td>
<td>0.022∠-81°</td>
<td>0.58∠23°</td>
</tr>
<tr>
<td>L6</td>
<td>0.013∠-58°</td>
<td>0.015∠-89°</td>
<td>0.84∠31°</td>
</tr>
</tbody>
</table>

The earth impedance of the lines varies from 0.58 to 0.84 $\Omega$. The earth impedance of L2 is 20% higher than that of L1 (Table 2). Results show that the multigrounded neutral constitutes an effective grounding system. Its effectiveness primarily stems from the contribution of customer grounds [2].

Figure 5 shows the EPR on the MGN of lines L1 and L2. More than 30% of the substation EPR appears on the MGN at 1 km. As it will be seen in section 2.3, higher soil resistivities contribute to increase both the EPR and the distances at which the voltages are transferred on MV and LV installations.

Figure 6: EPR along MV rural lines in high and low resistivities

Figure 7: EPR along the line (V/A)
Earth potential profile of substation grid compared to the EPR along the MV line L1

For comparison purposes, the calculated earth potential profile of a similar size grid in homogeneous soil is added in Figure 7. The distance required to reach 20% of the EPR more than doubles. However, whatever the characteristics of the soil, the potential on the MGN drops far more slowly than the potential at the surface of the soil. The concept of zone of influence is therefore not applicable if the telecommunication circuits share the earthing system of the MV network and/or the LV installations.

2.5 Touch voltages

MV/LV transformers in rural areas usually feed one to three customers. The length of LV cables is short and typically ranges between 15 and 100 m. The EPR on the MGN is therefore transferred in the LV installations without significant attenuation (see Figure 8). Touch voltages on the LV system ($U_{LV}$) are consequently similar to those on the MV system ($U_{MV}$).

Table 3 presents touch voltages measured between an earthed metallic structure and earth at a 1-m distance. The substation grid limits touch voltages to less than 20% of the EPR within the substation.

Touch voltages in LV installations close to the substation exceed 50% of the EPR and measured touch voltages in the installations up to 1 km are higher than those in the substation.

Due to the low soil resistivity, the maximum EPR in the substation is under 565 V (see section 2.1) and the touch voltages in LV installations are within acceptable limits.

3. CONCLUSIONS

In rural areas, the multigrounded neutral of MV lines transfer a significant fraction of the substation EPR over distances typically exceeding 1 km. Touch voltages in LV installations may exceed those occurring in the substation because they do not benefit from the potential equalizing effect of the grid.

Results show also that the multigrounded neutral constitutes an effective earthing system. MV lines, particularly in HV/MV substations, contribute to limit the EPR and touch voltages within safe limits. However, mitigation measures may be required in some cases particularly in high soil resistivity areas.

The concept of zone of influence is not applicable if the telecommunication circuits share the earthing system of the MV network and/or the LV installations. The connections between these systems are common in North America. Hydro-Québec is therefore planning a project aimed at reviewing the methods applied for the protection of telecommunication circuits entering substations.

4. REFERENCES

[1] IEEE Std367 1996: "IEEE Recommended practice for determining the electric power station ground potential rise and induced voltage from a power fault".


[4] ITU-T Recommendation: "Protection of telecommunication lines against harmful effects from electric power and electrified railway lines", Vol. II.