THE NEXT GENERATION LEASED LINE TELECOMMUNICATION PROTECTION FOR HIGH VOLTAGE SUBSTATION

By

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I hereby declare that I am the sole author of this thesis.

Section 3,4 and 5 on pg 17-30 are direct statements extracted without modification from Mr. Jean De Seve SES users group publication[10]

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ABSTRACT

Telecommunication circuits and leased lines have been in use for controlling substations for many years. These circuits have usually been engineered according to set standards, however recent studies have shown that the parameters used for engineering the telecommunication circuits have various design flaws that may put these circuits in jeopardy during a local substation fault. The existing protection scheme for Solar, wind and other relevant power generating farms are such that, if they lose communication with the local Utility Transmission Station (UTS), the UTS automatically trips a local breaker and knocks the generation plant off the grid, this could mean thousands of dollars in lost revenue for the generation company, hence even a minor flaw in the telecommunication circuits can have a significant impact on the substation control system. This case study reviews the challenges of designing these telecommunication circuits for control and monitoring of substations and also reviews the case study performed by Hydro Quebec on the concept of Zone of Influence. In addition this study also proposes an alternate telecommunication model that when implemented will be able to withstand all the challenges of designing a circuits for the high voltage substation.

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List of Abbreviations

AC	Alternate Current
CSA	Canadian Standards Association
DC	Direct Current
e911	Enhanced 9-1-1
ESA	Electrical Safety Authority
GPR	Ground Potential Rise
GS	Generating Station
HMI	Human Machine Interface
HV	High Voltage
IEEE	Institute of Electrical and Electronics Engineers
IESO	Independent Electricity System Operator
LV	Low Voltage
MS	Municipal Station
MV	Medium Voltage
RMS	root mean square
RTU	Remote Telemetry Units
SCADA	Personal Computer, a Desktop
TS	Transformer Station
ZOI	Zone of Influence

1. INTRODUCTION

Telecommunication circuits have been around since its invention in 1876 by Alexander Graham. Today the 2 or 4 wire telecommunication circuits are used to provide not only analog and digital voice communication, but also High speed Internet, Wireless data, Video and various other digital products. Telecommunication has become a very integral part of our society and is a part of the modern urban infrastructure. Telecommunication circuits are used to control traffic signals, identify location of caller through e911 and even to link intercontinental companies to one main storage or application server.

One of the other main usage of telecommunication circuits is to monitor and control utility transmission substation (TS), generating stations (GS), municipal station (MS) and other relevant substations using Supervisory Control And Data Acquisition (SCADA)[4]. In Ontario, the Independent Electricity System Operator (IESO) [5] connects to all participants - generators that produce electricity, transmitters that send it across the province, retailers that buy and sell it, industries and businesses that use it in large quantities and local distribution companies that deliver it to people's homes. The IESO monitors the system and identifies what is required to maintain reliability in the future, reporting on these recommendations through various publications. All the companies that make up the power system in Ontario must meet the IESO's standards.

Similar to the IESO, the power utility companies monitor their own inputs and outputs through SCADA. The primary purpose of SCADA is to monitor, control and alarm plant from a central location. There are three main elements to a SCADA system, telecommunication circuits, RTU's (Remote Telemetry Units) and HMI (Human Machine Interface). Each RTU effectively collects information at a site, while telecommunication bring that information from the various plant or regional RTU sites to a central location, and occasionally returns instructions to the RTU. The HMI, which is necessarily a desktop computer; displays this information in an easily understood graphics form, archives the data received, transmits alarms and permits operator control as required.

Since the substation where the RTU's are located can be kilometres away from one another, the power utility companies often lease telecommunication facilities from the local phone companies. The local phone companies place their own telecommunication cables between two or more substations in order to connect the local RTU's to the main SCADA monitoring system and are responsible for the management, maintenance and proper installations of these cables

Telecommunication facilities that serve electric power stations have to be robust and have to follow certain standards in order to be operational during a fault. In general the maximum allowable voltage on a regular telecommunication circuit servicing the public is approx 300V, beyond which the circuits do not operate. In a substation, during a line to ground fault, caused by a single phase or a three-phase conductor coming in contact with the neutral wire or the ground causes large currents to flows into earth through the ground grid of the substation thereby creating a Ground Potential Rise (GPR) at the substation. The potential at the substation relative to a distant point on the earth is highest at the point where current enters the ground, and declines with distance from the source. The effected location where the voltage is at its peak to the location where the fault voltage level has declined to 300V is known as the Zone of Influence (ZOI) boundary. Traditionally the ZOI boundary was thought to have a circular form , however resent case studies have proven otherwise

The GPR voltage during a fault period can be upto a maximum of 5000 V AC as per Electrical Safety Authority (ESA)[6] standards. Now if special consideration are not taken the telecommunication circuit will fail at the 300V level, which can be very dangerous, especially if these telecommunication circuits are vital to clear the fault at the substation. In addition IESO take their reading every 5 minutes, so if the fault exists over 5 minutes, it can jeopardize the IESO measurement for that station.

The GPR voltage varies from substation to substation, hence the telecommunication circuit protection requirement also vary from substation to substation. In order to accommodate this variances certain standards and practices have been established for the protection of the wire-line communication facilities serving these electric supply location. IEEE 367-1996[1] is one such standard that have been in place since 1996 and as of today majority of the telecommunication circuits used to provide service to power stations have been built using the parameters prescribed in the standard. In Canada, the Canadian Standards Association (CSA) 22.1 Section 60-204 [7] also establishes the protection requirement for telecommunication cables serving power stations.

As stated earlier, during a recent field experiment performed by Hydro Quebec [10], it has been observed that the calculation and the region for the ZOI that has been established in IEEE 367-1996 does not take into account certain variables that may put the telecommunication circuits serving these stations at risk of failure. This is a significant issue as the ZOI determines the nearest point where the telecommunication should be grounded to avoid interferences such as inductive and capacitive coupling. The report discusses the issues and challenges with the change in ZOI calculation and proposes a new design to overcome these challenges.

This report also analyses the effects of changes to the ZOI calculations on the telecommunication cable and circuits. The challenges include, effects on the cable passing through the ZOI, the effects on the circuit passing through the ZOI, adhering to standards and technology limitations. The project explores current method of protections inside the ZOI and the issues with this method. In addition the report also proposes a novel architecture to mitigate all these challenges through appropriate design and re arrangement of existing telecommunication technology.

The report is broken down into various section, the second section analyses the challenges of providing leased line telecommunication to high voltage power station and the effects on placing the telecommunication cable inside the ZOI. Section 3, defines the theoretical model developed by Hydro Quebec to analyze the effects of ZOI and section 4 discusses the field results from implementing the Hydro-Quebec model in the real word and reinforces the effects on the ZOI that are not included in the current IEEE Std. 367. In section 5, the current ZOI standard on IEEE Std 367 are analyzed and new standards are proposed based on the Hydro Quebec field study. Finally in section 6, a novel architecture of leased line telecommunication is proposed that overcomes all challenges discussed in previous sections and also takes into account the new proposed changes in IEEE std 367 in respect to the ZOI calculation. The report is concluded in section 7, followed by future work and references in section 8 and 9.

2. DESIGN CHALLENGE

The ZOI parameter has significant impact on how the telecommunication circuit to various substation are designed. Some of the effects that have to considered and become a design challenge are described below

2.1. Effects on Cable passing through the ZOI

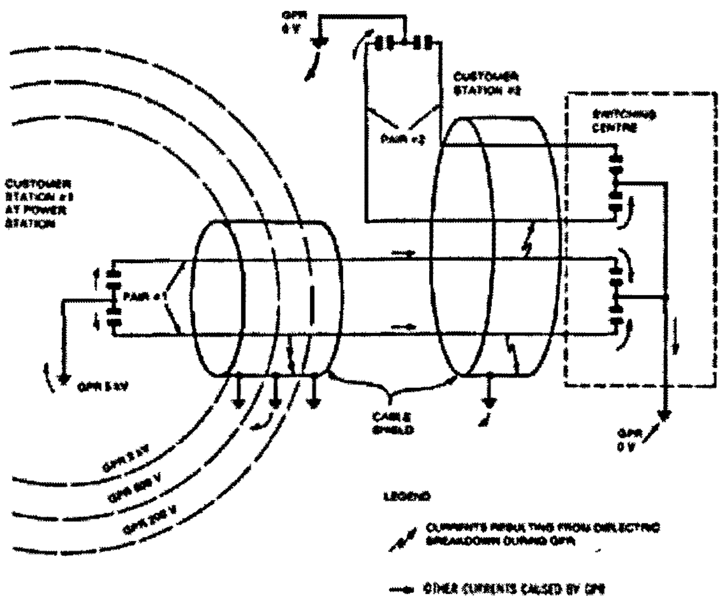

Figure 1: Effect of GPR on Cable Pairs
Source: IEEE 367-1996

Telecommunication cable pairs always have a "tip" and a "ring" side, the tip is usually connected to the ground at the central office. When a telecommunication buried cable with a metallic sheath is located in the vicinity of an High Voltage (HV) electric power station, a transmission line tower, or enters an electric power station, a part of the GPR of the HV system, as shown in Figure 1, is transferred to the electrode or sheath in the event of a fault to ground. In the case where the metallic sheath is not properly grounded, high potential around the cable can leap into the "tip" of the cable pairs and chart a path to ground towards the central office due to di-electric breakdown. This can not only damage the circuit but also cause a puncture (also known as a pinhole) in the cable sheath, exposing it to the elements and causing further damage.

One way to minimize this effect to ensure the metallic sheath is properly grounded outside the ZOI. This ensure the induced voltage has a path into ground prior to jumping onto the "tip" side of the cable pair causing a major disconnect.

2.2 Effects on the circuits passing through the Zone of influence:

When designing a telecommunication circuit that will provide service to power station we have to take into consideration interferences such as Inductive, Capacitive and resistive coupling in addition to lightning induced transient voltages.

Inductive Coupling: is the transfer of energy from the power line circuit to the telecommunication circuit by means of mutual inductance between the two circuits. Mutual Inductance occurs when a change in the current of one circuit affects the current and voltage in the other circuit located in close vicinity. Inductive coupling in telecommunication circuits produce noise in the line, thereby reducing the integrity of the circuit. Mutual Induction and the induced voltage can also be defined by the following formula[19]

$M = k\sqrt{L_1 L_2}$, *where* k *is the coefficeint of coupling and is in the range of* $0<k<1$

and N_1 *and* N_2 *are the number of turns of the cable*

$L_1 = \mu_0 N_1^2 \pi r^2 l$, l *is the length of the cable and* r *is the common radius*

$L_2 = \mu_0 N_2^2 \pi r^2 l$. μ_0 *is the permeability factor*

$V = -M \frac{dI_2}{dt}$. *Now according to Faraday's and Lenz's law, the induced voltage* V *on a conductor due to* I *on a nearby conductor*

Capacitive Coupling: When two conductors are parallel to one on another, there is a local static charge that starts accumulating between the parallel conductors provided atleast one conductor has a high voltage current flow through it. This charge can increase the voltage level at the point of occurrence and disrupt telecommunication transmission on especially on DC trip circuits. DC trip circuits are used to trip a transformer breakers and have a threshold voltage of 50V, so if the GPR at the local station is over 50V and those circuits are not protected properly from capacitive coupling it can easily knock a transformer station out of service.

Resistive coupling: This is actually a useful as well as disruptive type of coupling when it comes to telecommunication circuits. Resistive coupling can be used to dynamically reduce the voltage by increasing the resistance of the local telecommunication circuits. At the same time, if the resistance of the circuit becomes too high, it may increase the dB loss of the overall circuit loop to a point that eventually knocks off the data circuits that are vital for substation monitoring and control.

Lightening: Direct lightning hits cause the GPR to rise at a transient rate, so if proper protection is not taken the entire cable can be jeopardized as shown on Figure 2. In the picture, due to improper grounding, the "tip" side of the cable pair was the chosen path to ground for the lightning hit. Since the pairs are not designed to take on such a large voltage and current spike, the entire cable heated up causing burn marks along the path towards the central office. Figure 3 shows the entry point of the lighting and you can easily see the exposed copper pair that was used as the ground path.

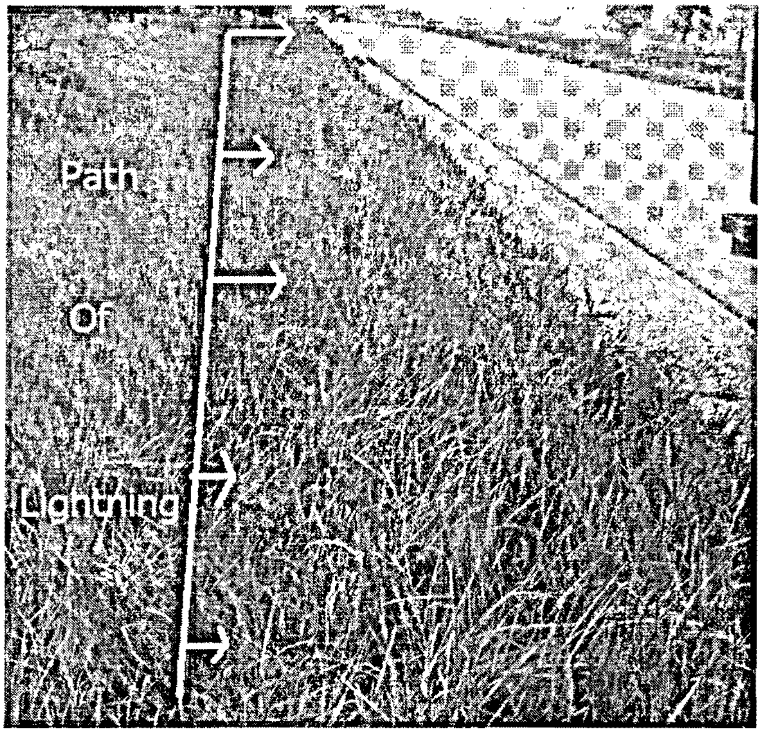

Figure 2: Path of lightning through underground buried cable Sheath

All these interferences can significantly jeopardize the integrity and reliability of the circuit thereby putting the stations it provides services to at risk. Determination of the ZOI effects how protection from each of these items are designed not only to protect the circuits providing service to the substation, but also to the local subscribers in and around the station.

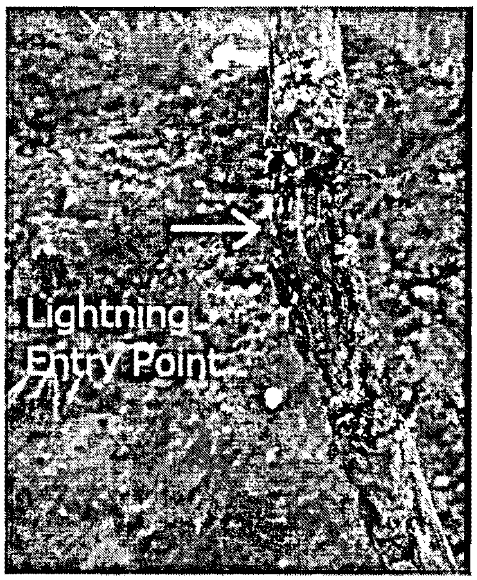

Figure 3: Lightning Entry Point into the "Tip"

2.3. Challenges of Adhering to standards

IEEE 487-2000 [2] defines the various classes of service performance objective (SPO) that are required at

Substation or Generating stations. When providing and designing circuits for power stations these standards have to be maintained.

Class A: Non-interruptible service performance (should function before during and after power fault condition)

Class B: Self-restoring interruptible service performance (should function before and after the power fault condition)

Class C: Interruptible service performance (can tolerate a station visit to restore service)

IEEE 487-2000[2] also defines the various level of protections required and categorizes them in three different voltage levels.

Voltage Level I: is the voltage level at which virtually no pair-to-pair or pair-to-shield dielectric failure would occur in cables serving the electric supply location that had not been specifically installed and tested as a dedicated high dielectric cable. If service should be continuous during the fault (SPO Class A) or restored immediately after the fault (SPO Class B), then consideration of the dielectric withstand capabilities of the elements of the plant is important. Experience has shown that the general-use telephone cable may fail in the pair-to-pair and pair-to-shield modes at the splices at voltages that exceed 300 V peak. Many administrations have chosen a value of 300 V, either rms or peak, as the upper limit for Voltage Level I.

Voltage Level II: The upper limit for Voltage Level II is 1000 V peak. It is based on experience and is considered to provide a suitable safety margin below voltage and current levels that would cause telephone-type protectors to fuse, explode, or cause fire hazards. In Voltage Level II, special protective devices are not required on electric supply location services, provided that momentary interruption of service can be tolerated during a power system fault (SPO Class B).

An upper limit of 1500*V* peak is suggested if remote protection is used at the junction of the dedicated and general-use cables.

Voltage Level III: Voltage Level III begins at the upper limits of Voltage Level II and requires special high-voltage protection such as isolation or neutralization, or both, for the protection of plant, personnel, and circuit integrity for all types of services and SPO classes.

Most of the substation in Canada require Class A service for tripping, mainly because during a Fault at the station is when they would like to be able to communicate with the station to trip a breaker or shut down a transformer and Class A service is usually continuous during the fault.

General use telecommunication circuit protection get activated at 300V, so if there over 300V on the pairs the protection equipment trips causing an open circuit on the telecommunication lines. This protection scheme works great for small Municipal Stations (MS) that connect to 27.6kV or 44kV feeder lines and have GPRs of 300V or below, and allows communication without interruption during a single phase to ground fault at the station.

For larger substation that connect to 230kV transmission lines the GPR is significantly larger than 1000V and an optical or transformer based protection is used as they fall under the Voltage Class III protection.

2.4. Technology and cost Challenges

The final challenge of designing a circuit to the power station is the technology limitations. Some of the oldest substations in Ontario still function on DC tripping as discussed previously, which mean upgrading these facilities to the new standard would mean extensive amount of capital investments. The newer substations work on tone tripping and generally use the ABB NSD570[8] for teleprotection and SCADA. In addition to all that, since majority of the control equipment such as the NSD 570 is housed inside the substation, they are prone to Electromagnetic fields (EMF) from the surrounding high current line. The EMF can trip sensitive circuits hence it is important to ensure the teleprotection equipments that are placed inside the substations are susceptible to EMF.

3. HYDRO QUEBEC FIELD TEST AND PROPOSED CHANGED TO ZOI CALCULATIONS

IEEE-367[1] recommendation covers the areas of GPR, induction and zone of influence (ZOI) calculations. All ZOI calculations examples and guidelines in the existing standards are based on power station grid without taking into account multigrounded line connections. Figure 4 shows an example of one of the proposed graphs recommended for ZOI evaluation. The ZOI boundary can be based on contact voltage as defined by IEEE-80[3] but Telecommunication companies as stated earlier usually use a fixed voltage value of 300 V as recommended in IEEE 487 [3].

Even if the aspect of transferred voltage on metallic objects around electrical substation is mentioned in a few clauses of IEEE-367, the subject is barely detailed. Conductive coupling between multigrounded power lines with substation's grid is completely ignored.

This proposed model being added in clause 9.5 of IEEE-367 shows the effect of mutual resistance between ground connections around substations and the impact on soil and transfer voltage, as well as system grounding impedances.

Field tests made by Hydro-Québec between 2004 and 2006 give results similar to those reached by the model. Line models were developed based on field tests information.

The proposed model modifies the application of the "zone of influence" concept in multigrounded neutral environments and shows that new guidelines must be added to standards like IEEE-367, 487 and 1590 [9], to cover the case of installations inside the zone of influence.

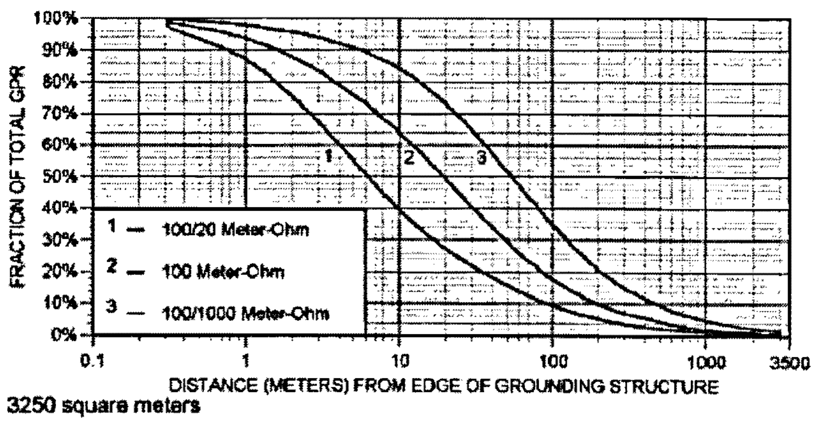

Figure 4: Ground Potential Graphn Example used for ZOI in IEEE - 367

3.1. SYSTEM DEVELOPMENT

This system was developed by Hydro-Quebec on HIFREQ to take into account conductive and inductive effects. A MALZ model was also done in order to show the inductive part on transfer voltage using HIFREQ/MALZ result comparison.

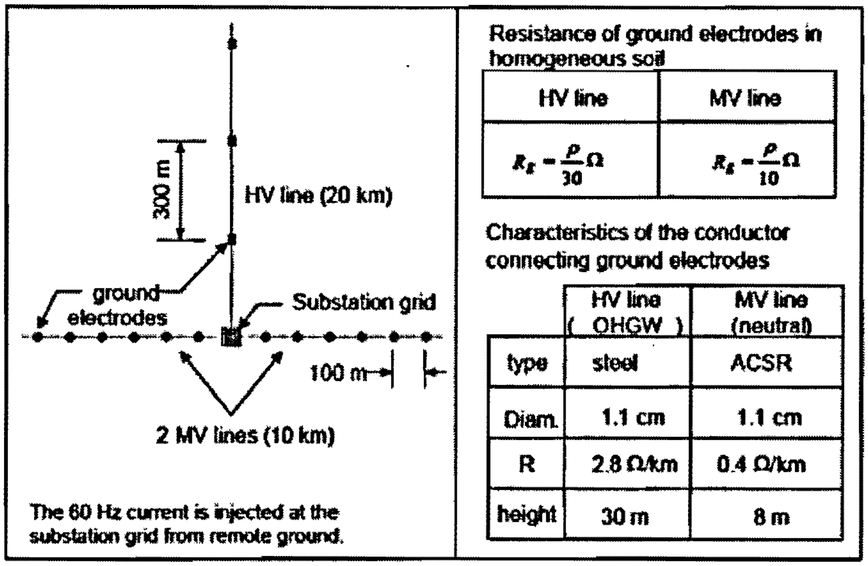

Figure 5: Hydro - Quebec Schematic for a rural Substation
Source: Proceeding from SES Group conference

Figure 5 presents the system considered in the calculation. The grounding system is comprised of the substation grid, an HV line and two medium-voltage (MV) lines. The MV line parameters are typical of rural North American overhead lines. In practice, MV lines possess multiple branches that are not represented to simplify the model. The frequency and resistance of the ground electrodes take into account the contribution of branches and customers. The current is injected in the substation grid from a remote ground.

Figures 6, 7 and 8 present the configurations of the substation grid, MV and HV lines. In the MALZ model, aerials conductors in figures 7 and 8 are replaced by coated conductors buried at 0,1 m.

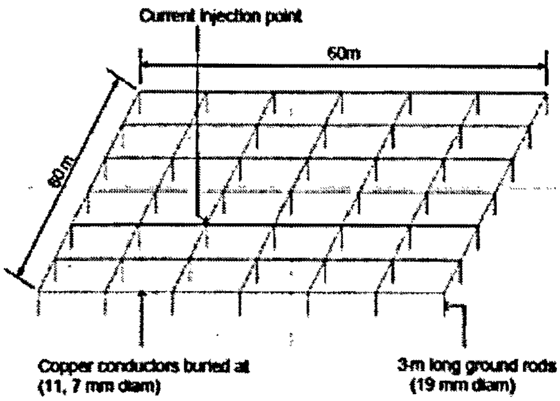

Figure 6: Configuration of the Substation Grid
Source: Proceedings from SES Group Conference

Two other kinds of conductors were also used to analyse the aspect of transfer voltage for the case of conductors nearby but not connected to the power station grid.

Conductor A: uncoated conductor (ex: pipe or lead sheathed cable in direct metallic contact with the soil)

Conductor B: coated conductor grounded at every 300 m (ex: underground polyethylene coated telephone cable.)

Calculations are performed for three soil structures:

- Homogeneous soil with a resistivity of 100 Ω·m
- First layer: 100 Ω·m (6 m deep), second layer: 20 Ω·m
- First layer: 300 Ω·m (6 m deep), second layer: 3 000 Ω·

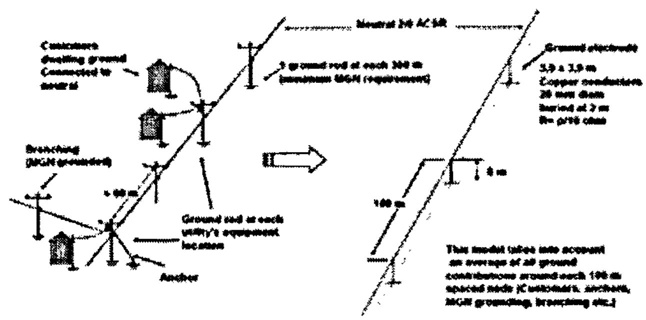

Figure 7: HIFREQ multigrounded neutral model of the MV line

Source: Proceedings from SES Group Conference

For the three soil structures, calculations are performed for the two following cases: the substation grid alone and the substation grid connected to the lines. Graphs present normalized voltages referred to maximum GPR for each case.

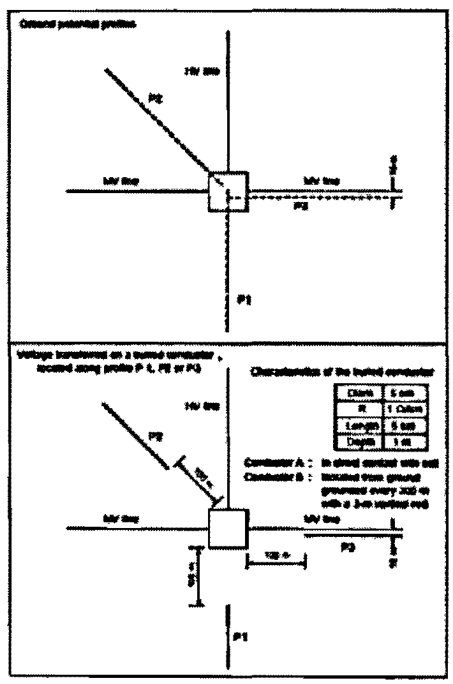

Figure 8: Location of calculated ground potential profiles and of the buried conductors used for the calculation of transferred voltages

Source: Proceedings from SES Group Conference

3.2. Theoretical Results

3.2.1 Impedance of the grounding system

As a first step, the current was injected in the 60x60 m substation grid alone. Table 1 show that the ground resistance varies between 0.3 and 9.6 Ω. With the lines included in the model, the impedance of the installation varies between 0.2 and 1.2 Ω. The reduction is more important at higher resistivity because the input impedance of lines is proportional to the square root of the soil resistivity whereas the resistance of the substation grid increases linearly with the soil resistivity. Consequently, the fraction of the total current in the substation grid reduces from 0.57 to 0.08 as the resistivity increases.

Due to the conductive coupling between the lines and the grid, the apparent resistance of the grid increases when the lines are present. For the 300/3 000 Ω·m case, the apparent resistance of the grid increases from 9.6 to 15.1 Ω.

The impedance of the MV lines is lower than that of the HV line because the serial impedance of the neutral is lower than that of the skywire (the ground resistance/km is similar).

3.2.2 Transferred voltage on the skywire and neutral

The lines are part of the grounding system of the installation and the skywire and neutrals transfer the GPR over large distances. Figure 9 presents the results. At 1 km from the substation, the voltage on the neutral varies between 40 and 75% of the GPR. Higher soil resistivities contribute to transfer the voltage over larger distances.

Table 1: Impedance of the grounding system

	Resistivity (Ω·m)		
	100/20	100	300/3000
Substation grid only			
GPR/I_{grid} (Ω)	0.32 ∠0°	0.76 ∠0°	9.6 ∠0°
Substation grid + lines			
I_{grid}/I_{total}	0.57 ∠13°	0.38 ∠18°	0.08 ∠28°
GPR/I_{grid} (Ω) GPR/I_{HV} (Ω) GPR/I_{MV} (1 line) (Ω)	0.35 ∠0° 2.2 ∠12° 1.1 ∠33°	0.82 ∠0° 2.4 ∠11° 1.2 ∠33°	15.1 ∠0° 6.5 ∠8° 3.2 ∠31°
Global impedance (Ω)	0.20 ∠13°	0.31 ∠18°	1.20 ∠24°

In MGN systems (customer ground connected to the power utility neutral), the voltage on the grounding system of customers located within a few hundred meters from the substation is a significant fraction of the substation GPR. As a consequence, for example, telephone circuits serving these customers experience similar overvoltage due to the GPR than those entering the substation.

Due to the higher resistance of the skywire, the voltage drops more rapidly than on the neutral. At 1 km from the substation, the voltage on the skywire varies between 15 and 60% of the GPR.

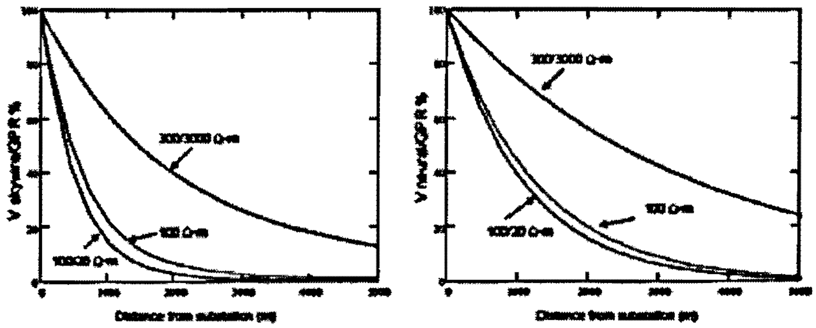

Figure 9: Transferred Voltages on the skywire and the neutrals

Source: Proceedings from SES Group Conference

3.3 Zone of influence of the installation

As stated earlier, when a fault occurs at the substation, the current is distributed between the substation grid and the ground electrodes along the lines. This distribution of the current between tens of electrodes covering a large area affects the zone of influence of the substation. This impact is greater for soil structures with a lower resistivity for the upper layer because it contributes to increase the conductive coupling between electrodes.

Figure 10 and 11 gives an example of 3D soil voltage profiles calculation for 100/20 Ω·m 300/3 000 Ω·m soils structures. In the 300/3 000 Ω·m case (figure 11) when the current is injected in the substation grid only, the potential is less than 10% of the GPR at 500 m and less than 5% at 1 km. The lines contribute to a significant increase of the potential at the surface of the soil. It reaches 30% of the GPR at 500 m and more than 20% at 1 km. In low soil resistivity as in the 100/20 Ω·m example, much lower conductive coupling does not affect significantly the soil voltage profile but, as seen on figure 8, GPR is transferred over the neutral connection on significant distance.

Detailed graphs of the three linear potential profiles using MALZ model (see Figure 8) are given in Figure 13. Only the conductive coupling is taken into account. The potentials are highly dependant on the soil structure. Without lines, for the base case (100 Ω·m), the potentials at 0.5 and 1 km are 5 and 2% of the GPR respectively. If the upper layer has a higher resistivity (100/20 Ω·m), the potentials are reduced to 2 and 1%. They are increased to 10 and 5% of the GPR respectively if the upper layer has a lower resistivity (300/3 000 Ω·m).

As shown in Figure 11, the lines contribute to significantly increase these potentials. At 1 km, potentials vary between 1 and 50% of the GPR depending on the soil structure and the location of the profile. As expected, the profile along the MV line (P3) produces the highest values. In most cases, potentials along profiles P1 and P2 are similar.

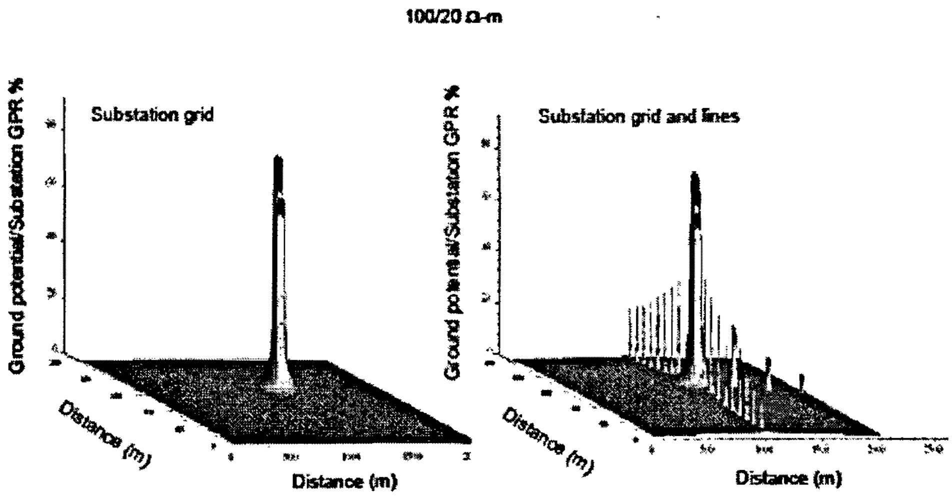

Figure 10 3D graph showing the zone of influence of the substation with and without lines for the 100/20 Ω·m soil structure

Source: Proceedins from SES Group Conference

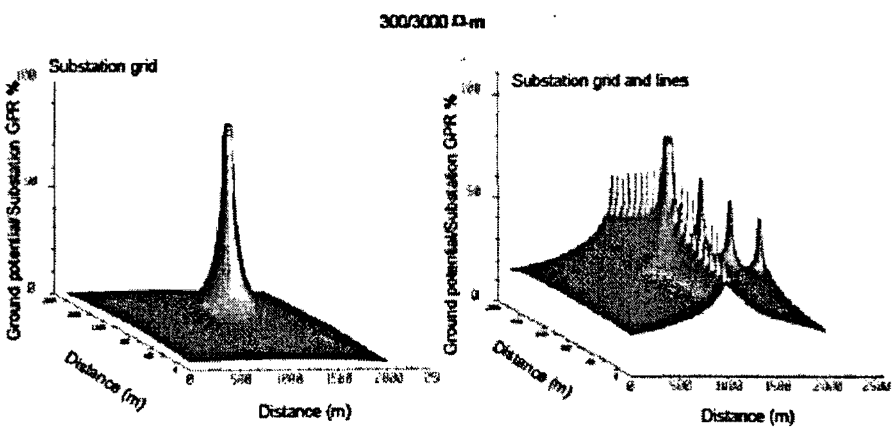

Figure 11 3D graph showing the zone of influence of the substation with and without lines for the 300/3 000 Ω·m soil structure

Source: Proceedings from the SES Group Conference

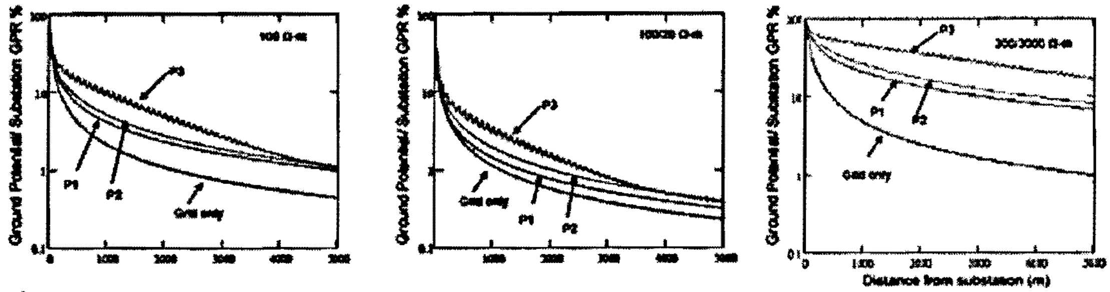

Figure 12 Ground potential profiles
Source: Proceedings from SES Group Conference

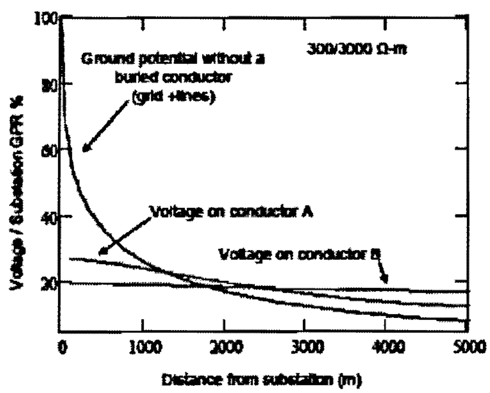

Figure 13 Voltages on buried conductors A and B along profile P2 for the 300/3 000 ρ-m soil structure
Source: Proceedings from SES Group Conference

3.4 Transferred voltages on a buried conductor

Since the lines have a significant impact on ground potentials, it can be expected that they will influence the transferred voltages on buried conductors. The voltage on the conductor is a fraction of the maximum ground potential seen along the route. Figure 13 gives an example of the voltage on conductor A or B buried along profile P2.

The ground potential without buried conductors reaches 60 % of the GPR 100 m from the substation but the maximum voltage reaches 28% and 20 % only on conductors A and B respectively. Voltage on conductor A is higher due to his low shunt resistance to ground. Voltage on conductor A would be reduced if it had a lower serial resistance.

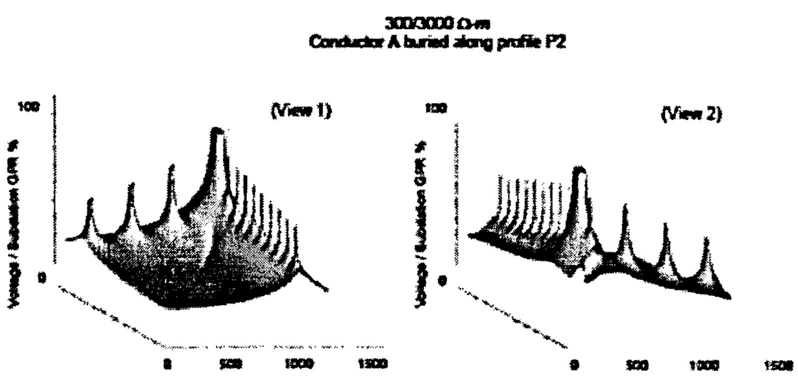

Figure 14 Influence on the ground potential of the buried conductor type along profile P2
Source: Proceedings from SES Group Conference

Currents in the buried conductor resulting from the variation in the ground potential along its length cause local deformations of the ground potential. Figure 13 gives an example for conductor

A buried along profile P2. The conductor causes a sharp decrease in the potential close to the substation. However, as shown in Figure 12, the potential increased at distances larger than 1.5 km.

The voltage on the conductor is systematically higher when the contribution of lines is taken into account. The increase is more substantial for soil structures that contribute to a higher conductive coupling.

As expected, the profile along the MV line (P3) produces the highest voltages on conductors. In most cases, voltages along profiles P1 and P2 are similar.

Table 2 summarizes the results. It compares the ground potentials to the voltages on the buried conductors and on the neutral. At 100 m from the substation, the voltage on the neutral of the MV line is above 90 % of the GPR.

Along profile P2, the ground potential at 100 m from the substation varies between 8 and 34 % of the GPR without lines and between 9 and 59 % if lines are included in the model. The voltage transferred on the conductor in direct contact with soil (A) is comprised between 4 and 27 % of the GPR whereas the voltage transferred on the conductor isolated from ground and grounded every 300 m (B) varies between 2 and 20 % of the GPR.

Table 2: **Comparison of the ground potentials and the voltages on the buried conductors and the neutral (100 m from the substation) (percentage of the substation GPR)**

Resistivity (Ω·m)	Ground potential (profile P2)		Voltage[1] on the buried conductor (profile P2)		Voltage[2] on the neutral of an MV line
	Grid only	Grid+lines	Conductor A	Conductor B	
100/20	8	9	4	2	90
100	16	22	10	5	92
300/3000	34	59	27	20	97

[1] Maximum voltage (at 100 m from the substation) (lines are included in the model)

[2] Voltage at 100 m from the substation

3.5 Combined effects of conductive and inductive coupling on buried conductors

Only the conductive coupling was taken into account in the MALZ calculations presented up to this point. With a view to estimate the contribution of the inductive coupling on the voltage on buried conductors, a HIFREQ model was used for the calculations of the conductor buried along profile P3. In that case, the conductor is parallel to the MV line at a horizontal distance of 15 m. The inductive coupling is the strongest for this profile.

Figure 15 presents the results. In this example, the inductive coupling contributes to increase the voltage on the conductor. On conductor A, the inductive coupling adds 5 % of the GPR approximately to the voltage on the conductor. On conductor B, 10 % of the GPR is added to the voltage. The smaller increase for conductor A is due to the lower resistance to ground along the conductor.

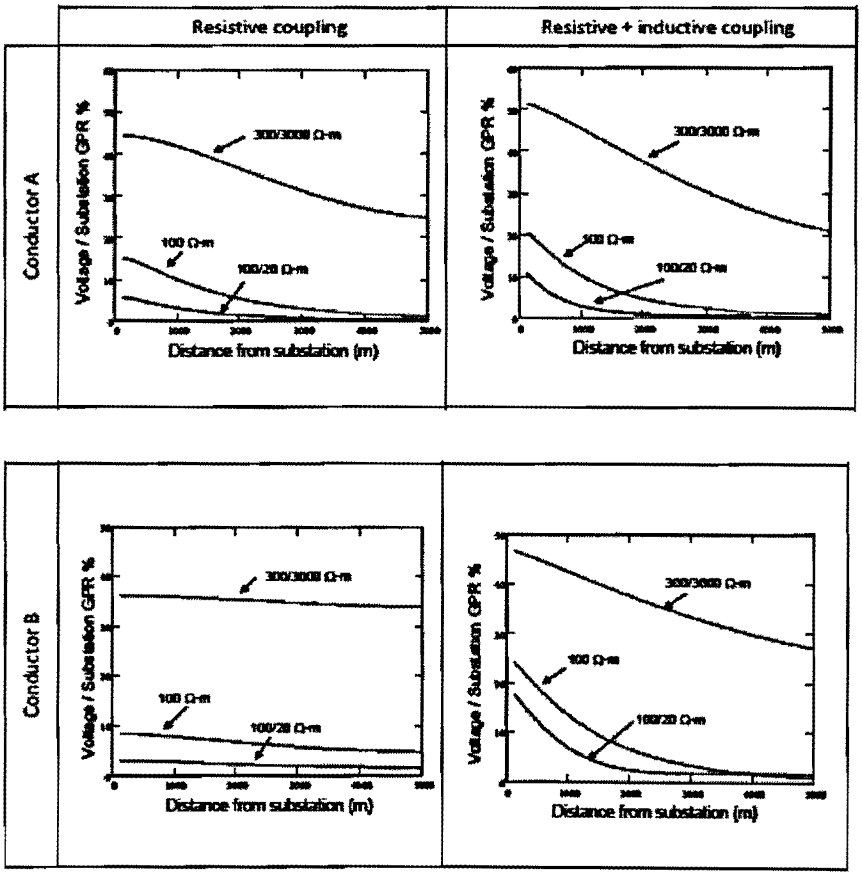

Figure 15: Impact on the inductive coupling on the voltage of the conductors A and B buried along profile P3

Source: Proceedings from the SES Group Conference

4 Field tests results comparison with HIFREQ model [10]

4.1 Field tests results

Field tests were performed by Hydro-Québec in 2004, 2005 and 2006 in two 120/25 kV rural distribution substations. One substation (Arthabaska) was located in a low soil resistivity zone and the other (Annonciation) in high soil resistivity zone The main objective of these tests was to evaluate different protection schemes for telephone cables serving substation during HV or MV faults.

Potential of the soil surface as well as current and voltage along common use line were measured on an area covering up to 100 km^2 around the current injection point. Complete test information can be found in CEATI[13] report no. T07300-3049 entitled "Electrical Protection of Telephone Cables Serving Substations".

HV faults were simulated by injecting 50 Hz and 70 Hz current on a de-energized HV line using the same route of a real faulted line between two substations.

The resistivity structure at Annonciation area with top soil layer much lower than the rocky deeper layer produce a very large zone of influence as shown in clause 3.3.

Soil resistivity measurements made at twelve different locations on a 4 km^2 zone around the substation show wide lateral et vertical variations in soil resistivity. Compilation of two layer models results using RESAP module gives theses values:

- First layer resistivity ranging between 275 Ω-m to 1200 Ω-m
- First layer depth ranging between 0 to 4 m
- Deep layer resistivity ranging between 2400 Ω-m to 17000 Ω-m

Soil model (average on 4 km²):
First layer: 275 Ω·m -1200 Ω·m
Depth: 0 to 4 m
Second layer: 2400-17000 Ω·m

Maximum fault current for GPR evaluation: 3,6 kA

Zglobal: 0,734 ohm (measured)

point#	D (m)	GPR (kV)
1	0	2,64
2	150	2,52¹
3	900	1,96
4	2300	1,39
5	5000	1,16
7	8500	0,15
ΔV1-6	------	1,57
ΔV1-4	——	1,35

300 V ZI ≈8 km

Note 1: Actual ZOI based on grid only parameters

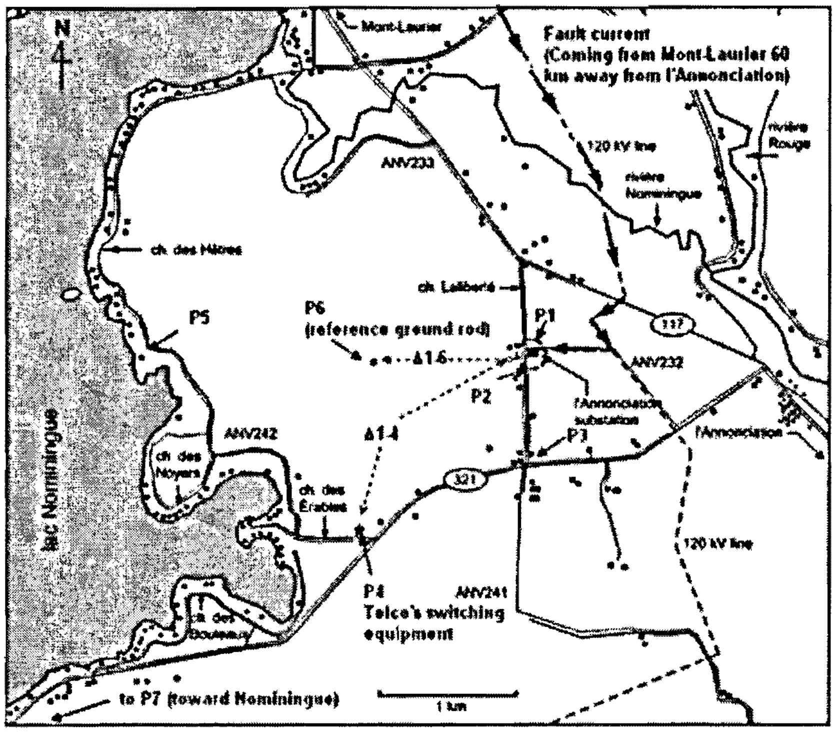

Figure 16: Hydro Quebec Field Test Result

Source: Proceedings from the SES Group Conference

Table on figure 16 show measured values of soil and neutral voltage around Annonciation substation (points numbered P1 to P7). Point 1 is the substation (at D=0 m). The measured global impedance of the global grounding system including all lines connexion was 0,734 ohms. The maximum fault current estimated at 3,6 kA gives an expected maximum GPR of 2,64 kV.

Point 6 is a reference ground rod first installed at 1,2 km from the substation for GPR measurement. Tests show that point 6 was not a 0 volt reference point. The "true" zero volt reference used for GPR evaluation was based on measurements and calculations of neutral voltage drop. As some errors may be introduced in the calculation of neutral series impedance, it is expected that the actual impedance (and then GPR) may be slightly higher than 0,734 ohms.

Current is measured on the neutral up to 8,5 km from the substation. Customers and Telcos equipment along the common use line are subject to induced voltages over this distance. They are also exposed to transferred voltages on the neutral higher than 1 kV up to 5 km from the substation.

It has to be noted that the zone of influence calculated for the local Telco without taking into account lines connections was 150 m (P2). The GPR transferred at the Telco zone of influence limit is 95 % of the substation GPR. The Telco's commutation equipment located 2,3 km from substation (P4) is at 53 % of the substation GPR. The 300 V limit on the neutral of distribution lines was evaluated to be at more than 8 km from the substation. The shield of telecom cables on these lines are connected to the neutral at every 300 m.

Telco cable shield and telecommunication services supplied to Annonciation substation were isolated inside the 150 m zone of influence to prevent transfer voltage on the telecommunication network as recommended by IEEE-487.

Obviously this isolation concept is useless to prevent transfer voltage on a multigrounded neutral network. The Annonciation case was selected for comparison with HIFREQ model.

5 Guideline proposed to IEEE 367 based on Hydro-Quebec experiments

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Two main observations can be drawn base on model and test results:

- The distribution grounding system carries a significant fraction of the fault current. The distribution network can therefore significantly affect the ZOI of the substation. For telephone cables not sharing the same structures as distribution lines, the concept of ZOI is applicable in principle; however, the calculation of the ZOI should include the contribution of the distribution lines.
- The neutral of distribution lines transfer the substation GPR over large distances. The ZOI concept is therefore non-applicable for the protection of telephone cable sharing the same structure as a distribution line.

In light of these observations, guidelines were proposed to be included in the next IEEE-367 revision:

- *"As formerly mentioned at article 9.5.3 the zone of influence concept is practically inapplicable for telecommunication cable sharing the same structures as distribution lines (common use lines). As shown in table 11 the 300 V point for a 1 kV GPR extend from 1.3 to 4.2 km to the substation. Considering that all customers served by telecommunication cables inside that zone are referenced to the MGN network, metallic isolation over such distances is unrealistic. Touch voltage mitigation (see IEEE-80) appears to be a more appropriate solution..."*

6. Effect on telecommunication industry

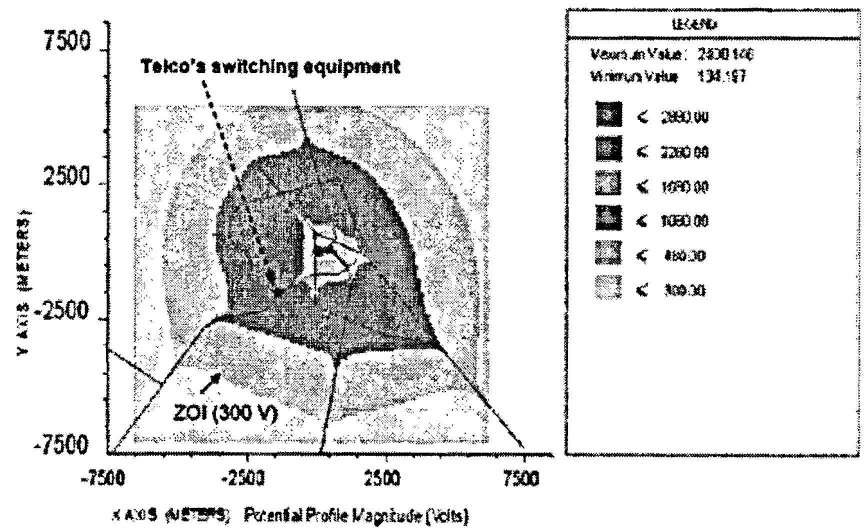


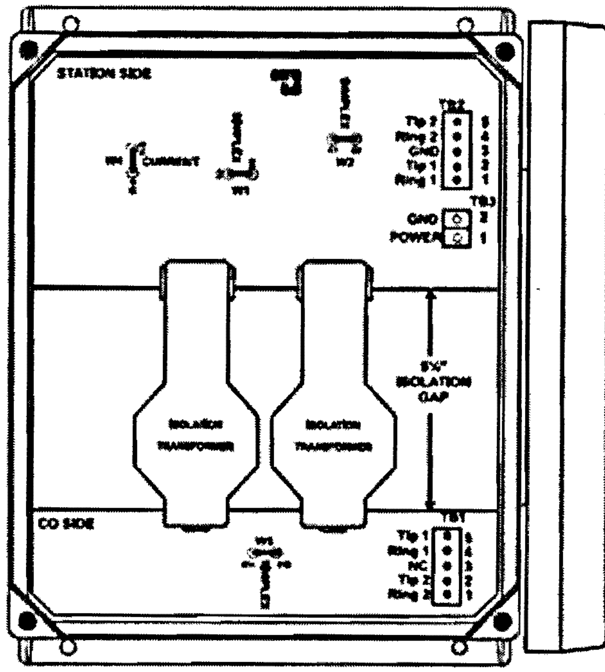
Figure 17: Soil GPR Profile
Source: Proceedings from the SES Group Conference

As stated by Hydro-Quebec the proposed changes to the ZOI effects the telecommunication industry is various ways. The effects on GPR along utility conductors at are on HV lines or in sections without neutral is not a concern because Telecommunication carriers usually do not joint build in these infrastructure. But on Medium and Low voltage lines this is an issue since some ZOI can extend over 8km as shown on Figure 17 from the main substation grid, the fault originating in a High Voltage substation with GPR over 1500V can trip a Low Voltage Local Municipal Station with GPR below 300V with no special Telecommunication protection. The main reason this can happen is because of induced voltage on the telecommunication shield from the bonds that are connected to utility Multigrounded Neutrals (MGN) along a low Voltage utility line.

In order to overcome this there are two solutions, since majority of the substation require SPO Class A service, the placement a special isolation transformer in all these substations regardless of GPR will ensure operation at the circuit level even when GPR is above 300V. Figure 18 shows the an example of a transformer based isolation protection unit. Communication maintained across the gap by isolation transformers that provide low-loss low-distortion transmission.

Figure 18: Model 751228SP Component Layout (only major components shown)

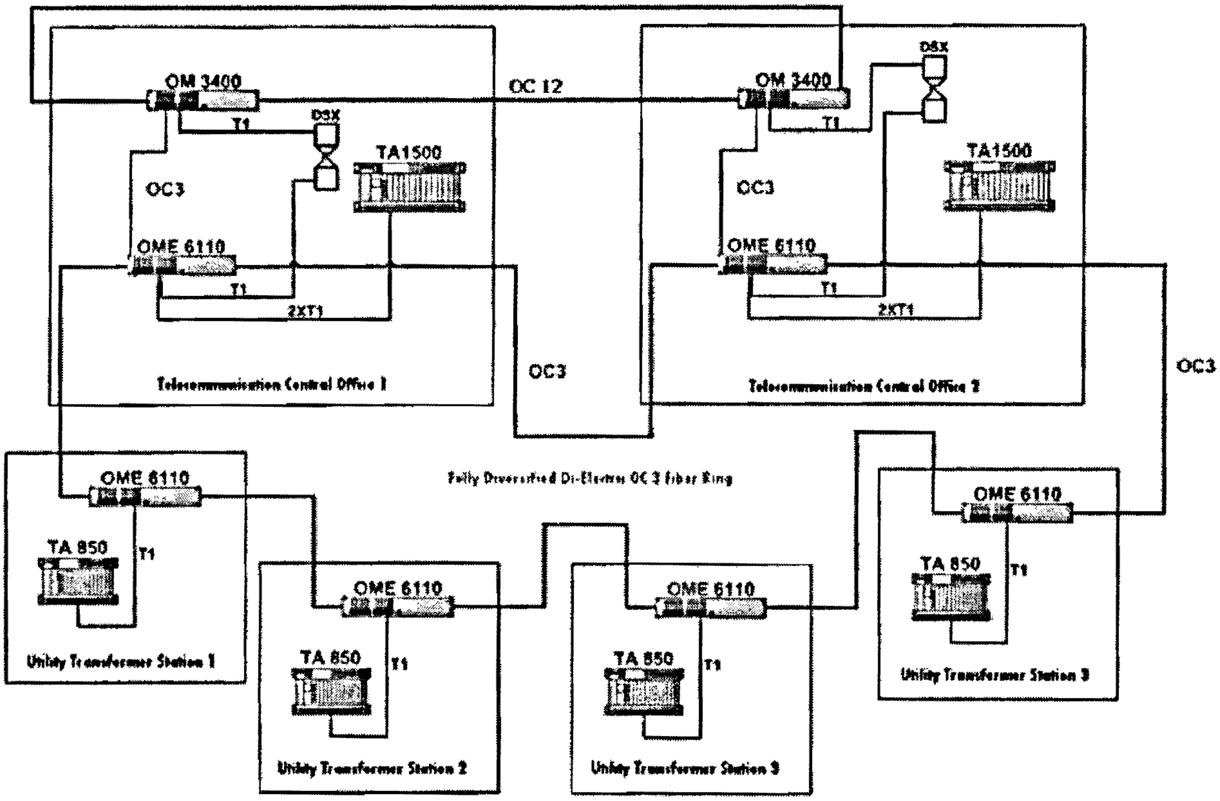
Source: www.positronpower.com



This is a very critical recommendation for the new Green energy initiative, as majority of the Wind and Solar farms have GPR at the 300V range due to their large ground grids footprints. And the protection scheme for these farms is such that, if they lose communication with the local Utility Transmission Station (UTS), the UTS automatically trips a local breaker and knocks the generation plant off the grid, which could mean thousands of dollars in lost revenue for the generation company. Although this will mainly take care of the induced voltages in the physical pairs, there is still the issue of dielectric breakdown of the cable passing through the ZOI that may occur and cause circuit disruption.

To overcome the dielectric breakdown issue, the second solution is to provide dielectric fiber solution to High voltage substation. A typical substation require 3~4 Voice line for SCADA, 911 and other monitoring service and 1 ~2 Partial T1 (64k) for IESO and Telemetry. These can be easily provided over a fiber based solution as shown below. The dielectric ring is prone to resistive, capacitive and mutual inductance and also is prone to lightning. Furthermore proposed Optera Metro 3400[11] along with the Optera Metro 6110 and the Adtran 1500 is robust enough to be placed inside a control building without any issued especially when used in conjunction with the ABB NSD 570.

Figure 19: Di-Electric OC3 Fiber Ring, with Full Diversity



An OC 3 (155 Mbps) bandwidth can provide upto 84 T1 or 2016 DSO. A DSO is 64Kbps or voice grade typically known as a phone line. So if we assume 2 Full T1's (2 x 1.544 Mbps) per utility station, a typical OC3 ring can provide service to approx 42 Stations. The fiber ring provides diversity and can be made redundant i.e in case of service failure to one fiber feed, the traffic is automatically routed to the alternate side of the ring and there is no service disruption.

The isolation protection units currently being deployed in Substations cost around $10,000 to $15,000 with individual isolation cards ranging from $1,500 to $3,000 range. If you take those into consideration an OC3 unit cost only $15,000, so the upfront cost is fairly comparable.

Furthermore this can also reduce the cost to utility station, as whole sale T1 is much cheaper than purchasing individual DS0

Finally, since the fiber is completely Dielectric, there is no transfer of Voltage or current and the fiber can be lashed on the same pole as the Medium Voltage lines running out of the utility substation without any effects of GPR.

This is one of a kind model and is currently being proposed in a mine in Northern Ontario, and is being reviewed for installation and standardization in new telecommunication substations in the region.

7. CONCLUSION

This report looks at the proposed changed on IEEE Std. 367 standard specifically the parameters around Zone of Influence calculation, and its impact on telecommunication lines providing service to substation, wind farms, solar farms etc. The report provided support based on the Hydro-Quebec field test results and telecommunication and electrical principles

The first conclusion of the presented study recommends placement of a special isolation protection unit to all utility stations that have a SPO Class A requirement regardless of the GPR at these locations.

The second conclusion describes an alternate to copper design i.e a di-electric fiber network design, that can withstand the effects of the GPR, and provide diverse protection to telecommunication circuits providing service to utility substation. This not only provided a superior and more reliable source of telecommunication service but is also prone to all electrical effects such as capacitive, inductive and resistive coupling.

8. FUTURE WORK

The future work on this project would be to look at the EMF emitted from copper telecommunication cables [14] and support structures that are providing service to substation. In the City of Toronto, there are certain EMF criteria's [16] that have to be satisfied, and with the change of the ZOI calculation, the enlarged ZOI boundary can cause above normal EMF emission on from the telecommunication infrastructure. If this can be proved, then several telecommunication infrastructures providing services to substation can be forced to changed to the di-electric model as proposed in this report.

This work is very lucrative as it falls under the "applied research" category of the Scientific Research and Experimental Development (SR&ED) program and can be funded through the federal government.

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