Proceedings of the Fourth IASTED International Conference
POWER AND ENERGY SYSTEMS (AsiaPES 2008)
April 2-4, 2008 Langkawi, Malaysia
ISBN CD: 978-0-88986-732-1

EFFECTS OF SEASONAL VARIATIONS ON HIGH VOLTAGE SUBSTATION GROUNDING GRIDS – MEASURED AND COMPUTED RESULTS

Sharon Tee Farid Paul Dawalibi
Safe Engineering Services & technologies ltd.
1544 Viel, Montreal,
Quebec, Canada
sharon.tee@sestech.com farid.dawalibi@sestech.com

Robert Yonza
Manitoba Hydro
1140 Waverly Street, Winnipeg,
Manitoba, Canada
ryonza@hydro.mb.ca

ABSTRACT

The primary objective of this paper is to realistically assess the impact on the overall ground system performance and measurements of a transmission station due to a complex environment including; a very inhomogeneous soil structure, a microwave site, an auxiliary ground site, a nearby lake and slag pool, multiple transmission line equipped with skywires, a distribution line neutral, pole grounds and a neighbouring town distribution network while accounting for significant seasonal resistivity variations of top soil layers as required by IEC Standard 61936-1. Since the present North American high voltage substation grounding standards (ANSI/ IEEE Standards 80 and 665, respectively) do not directly address this issue and very little information exists in other grounding literature, this study focuses on the behaviour and safety of the grounding system in summer, winter and spring soil conditions.

KEY WORDS

Substation Grounding, Seasonal Resistivity Variations, Electric Safety

1. Introduction

Over the next few years, Herblet Lake Station will experience a major expansion to the number of its 230 and 115 kV transmission lines which will increase its short circuit capacity significantly. The expansion was expected to burden the existing grounding system and, in order to avoid unnecessary costly upgrades, Manitoba Hydro conducted thorough resistivity and Fall of Potential (FOP) measurements at the station such that it could be modeled without unreasonable assumptions and therefore, avoid unnecessarily casting doubt on the performance of the overall system. The present grounding system was installed connected to an auxiliary ground grid in order to enhance the overall performance of the system. This auxiliary grid was buried in a pond a few hundred meters away from and connected to the main ground grid. Further complications to the grounding model include: a microwave site, a nearby lake and slag pool, multiple transmission line equipped with skywires, a distribution line neutral, pole grounds and a neighbouring town distribution network (see Figure 1).

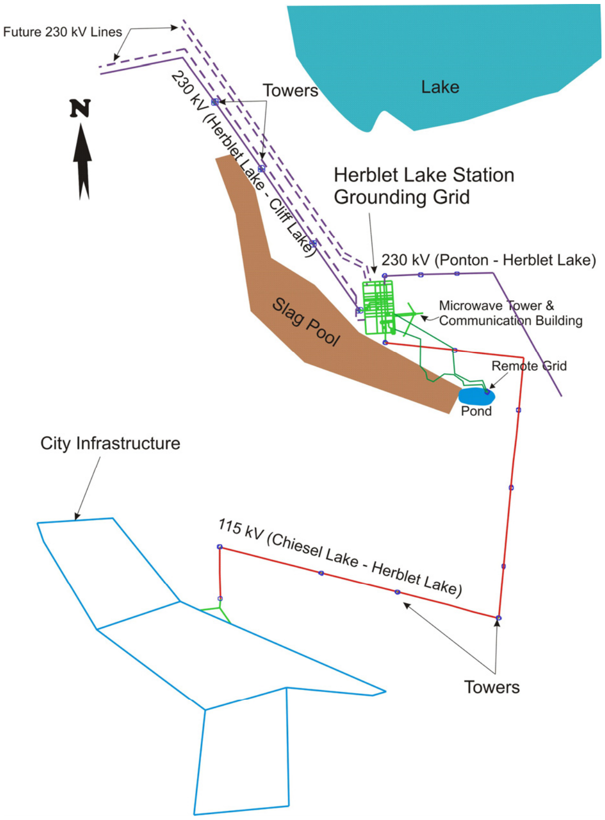

Figure 1: Plan View of Herblet Lake Station and Surrounding Grounding Network

2. Measured and Computed Results Analysis

2.1 Soil Resistivity Measurement and Interpretation

Soil models were developed based on a large number of soil measurement traverses taken in and around the station (see Figure 2). The short traverse measurements within the station were selected in order to sample shallow soil layers while the two long measurement traverses, located outside the station fence have been made to provide a representative sample of soil resistivities at greater depths.

The soil resistivity analysis which was conducted using the MultiGroundZ [1] software package, revealed two limiting multilayer soil model structures and an average one as shown in Figure 2 and Table 1.

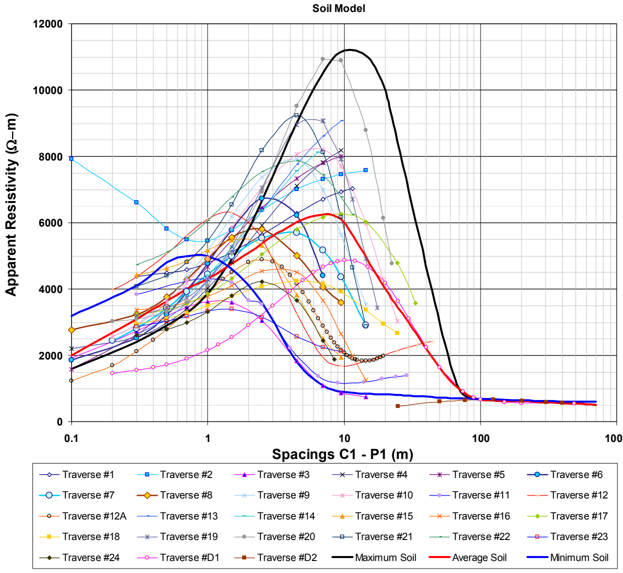

Figure 2: Equivalent RESAP Soil Model Comparison

Table 1: Soil Models

Soil Model	Layer	Resistivity (Ω-m)	Thickness (m)
Maximum	**1**	**1600**	**0.44**
	2	**15293**	**12.3**
	3	**552.8**	**∞**
Average	**1**	**2000**	**0.26**
	2	**6127.7**	**15.43**
	3	**571.1**	**∞**
Minimum (Summer)	**1**	**3200**	**0.25**
	2	**6000**	**1.36**
	3	**700**	**∞**

2.2 Seasonal Soil Characteristics Variations

The Fall of Potential (FOP) analysis presented in Section 2.3 validates the 3 chosen soil models and determines an equivalent soil structure model that best fits the measurements. As it turns out, the “Minimum” Soil model matches well the measured overall grounding network impedance. Therefore, the “Minimum” Soil model shown in Table 2 was chosen as the equivalent summer soil model that is used in Section 2.6 to perform the safety analysis of the station. Note that the label “Maximum”, “Average” or “Minimum” is used here to indicate the value of the center layer and should not be construed as having any particular meaning or attributes (6000 is rather very close to 6127.7 when compared to 15293).

It is important to note that soil resistivity varies throughout the year, with both moisture content and soil temperature affecting soil resistivity. Manitoba Hydro safety analysis specification requires that the “worst” case conditions be modeled. This is consistent with the IEC Standard 61936-1 [2] specific requirements and indirectly with IEEE Guide 80 and 665 general guidelines [3, 4]. The worst case safety scenario is considered to occur in the spring when the top layer is wet from melted snow while the ground grid remains in frozen soil in northern countries or in very dry soils after a sudden rain fall [5]. It is known that resistivity increases exponentially as temperature drops below freezing. Frozen soil will have a varying resistivity that is lower in magnitude at both the top and bottom frost line boundaries as opposed to the middle of the frost layer. To account for this effect, two additional soil conditions were analyzed: winter and spring.

Table 2: Selected Soil Model

Layer	Resistivity (Ohm-m)	Thickness (m)
1	3200	0.25
2	6000	1.36
3	700	∞

The most appropriate winter soil model to use in the absence of direct measurements is a challenging question. It is well known that soil resistivity increases dramatically when the temperature drops below zero degrees Celsius. The resistivity can increase by a factor of 5 to 1000 times the summer value, depending on the temperature drop, soil material type, moisture content, salinity, etc. What resistivity scaling factors should be used for the various top soil layers that are affected by the temperature in a given geographical region when soil freezes in a grounding analysis study? In the absence of specific data, SES-Soil-Manager, a component of the MultiGround family software packages, can provide accurate information once the nature of the shallow soil material is known.

At Herblet Lake Station however, both winter and summer soil measurement results were available for Traverse 12A (taken inside the station). Figure 3 shows the measured and computed apparent resistivity curves (based on the equivalent soil model for traverse 12A) for both summer and winter conditions. The equivalent computed soil structures are presented in Table 3. By comparing the top layer resistivity for summer and winter conditions (Traverse 12A), one concludes that the resistivity scaling factor is about 47 times higher in winter conditions than in summer conditions (784 compared to 37364 Ω-m).

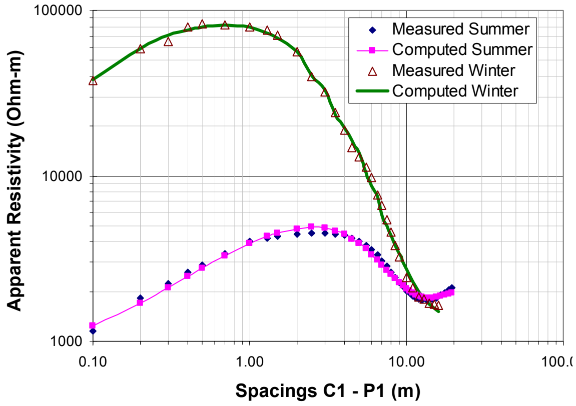

Figure 3: Apparent Seasonal Soil Resistivity Variations

2.3 Fall of Potential Measurement and Interpretation

Figure 4 shows the measured and computed FOP curves at a 70 Hz test frequency for one of the measured FOP profiles. Clearly, the so-called "Minimum" soil model matches quite well the measured values and therefore was selected as the base summer soil model structure to perform the station ground grid performance analysis described hereafter.

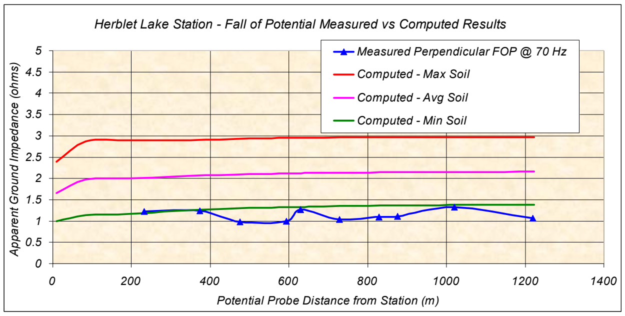

Figure 4: Apparent Seasonal Soil Resistivity Variations

2.4 Station Grounding System Impedance

In order to compute touch and step voltages associated with the Herblet Lake grounding grid, the system illustrated in Figure 1 was modeled with MultiGroundZ (initially and when necessary) and with MultiGround [1] as appropriate, in order to accelerate computation time, particularly for the spring and winter soil models. This approach is fully justified because the station grounding grid is moderate in size and is buried in high resistivity soil layers. Consequently, the grid is essentially an equipotential structure at 60 Hz. Therefore, both packages give very similar results in this case.

The overhead ground wires, transmission line tower grounds and city infrastructure grounds were included initially during the FOP measurement interpretations that require the use of MultiGroundZ. During the ground grid safety analysis that were carried out using MultiGround these were not included because their contributions are already considered in the fault current distribution analysis described in section 2.5. Table 3 presents the computed station grid impedance (including the microwave site and remote grid) under the various soil conditions examined. The values in this table were used for the fault current distribution analysis which is presented in section 2.5. Note that when new conductors are added to the existing grid, its ground impedance will decrease. Therefore, this new lower value must (and has been) used in the fault current distribution analysis.

Table 3: Station Ground Grid Impedance

Soil Model	Ground Impedance (Ω)
Summer	1.62
Spring	5.65
Winter	7.75

The analysis revealed that the existing conductor layout does not meet the safety criteria specified by Manitoba Hydro for the Present and Horizon (20 years) fault level scenarios if the resistivity of the surface layer of the crushed rock when wet is 3,000 ohm-m, a standard Manitoba Hydro requirement.

In this latter case significant changes and upgrades were required and will have to be recommended. This conclusion has been drawn following several computer analyses based on grounding network scenarios that rely on mitigation methods other than adding ground conductors within the substation perimeter fence. All scenarios analysed failed to reduce touch voltages within the prescribed safety limits. A summary of the cases that were analysed is provided in Section 2.6. Touch voltages within the station exhibit large values in zones where the grid mesh is too wide. This is mainly due to the soil structure (high resistivity surface layers over a significantly lower soil resistivity layers).

The main reason for the difficulties encountered in the design of a safe substation grounding using a strategy that focuses on reducing the ground impedance of the entire ground network as seen from the station is the slow decay of the ground potential rise (GPR) as a function of the overall ground impedance as shown in Figure 5. This figure was generated based on a detailed parametric analysis that became necessary in order to explain these difficulties.

Figure 5 shows that the station GPR decreases slowly from a maximum of about 2.5 kV to about 2 kV as the impedance is decreased from a very large value to about 1.0 ohm, a rather marginal GPR reduction considering the significant decrease in the impedance. Keep in mind that the existing minimum overall ground impedance of the station (not including overhead transmission and distribution lines) is over 1.6 ohms in summer. The installation of a grounding grid in the remote large pond (220mx100m) barely manages to reduce this impedance to about 1 ohm in summer. Further reduction of this impedance is simply not economical.

However, if the resistivity of the surface layer of crushed rock when wet is significantly larger than 3,000 ohm-m and the drainage in the station is such that standing water is not a problem, then the present station grounding grid design or a slightly reinforced one would meet all safety requirements at present and in the future and no special actions will be required. Considering that the native shallow depth soil resistivities as measured within and around the station were quite high even during summer conditions, it was suspected that the surface crushed rock resistivity could be significantly higher than the standard 3,000 ohm-m, typically required by Manitoba Hydro. Consequently, measurements of the wet crushed rock surface layer of the station became a critical item that was required before proceeding with any expensive mitigation measure. Therefore Manitoba Hydro requested that such measurements be carried out.

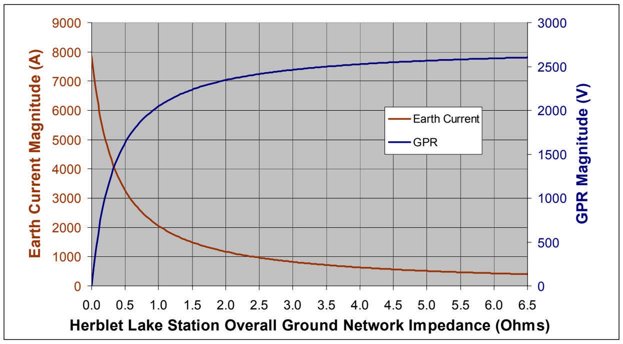

Figure 5: Ground Grid GPR and Earth Current as a Function of Ground Grid Resistance

The shape of the GPR curve in Figure 5 is not surprising if we note the following facts (see the illustration shown in Figure 6):

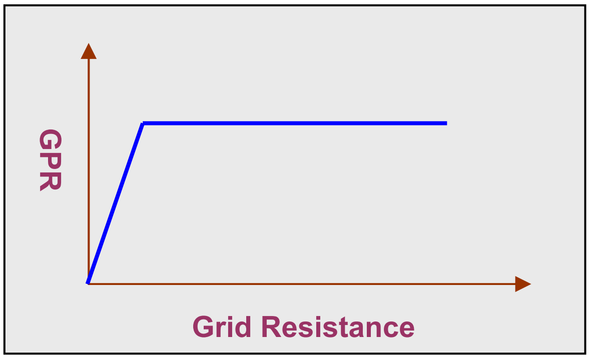

Figure 6: Illustration of Ground Grid GPR as a Function of its Resistance

- When the impedance of the grounding system is small compared to the equivalent ground impedance of all transmission line structures and shield wire return paths, the fault current is essentially dissipated in the grounding system and the GPR is proportional to the grounding impedance (rising linear portion of the curve). This is also true if the impedance of the equivalent ground return path is very large or infinite.
- When the impedance of the grounding system is large compared to the other transmission line return paths, the GPR is essentially limited by the equivalent impedance of the return path multiplied by the fault current (horizontal portion of the curve).

2.5 Fault Current Distribution Analysis

This section determines the fault current distribution between the grounding system and all other metallic paths such as sky wires or shield wires, neutral wires and other distant grounds that can divert some current away from the substation. All these alternate paths return fault currents to remote sources, Currents originating from local sources circulate within the grid conductors. Ground Potential Rise (GPR), Ground Potential Differences (GPD), touch and step voltages will develop within and outside the substation as a result of the currents flowing along and leaking out of the ground conductors. The safety analysis described in Section 2.6 relies entirely on the accurate assessment of this fault current distribution as described in this section. In-service-date (ISD or present condition) and 20 year Horizon single-line-to-ground (SLG, 230 kV) faults were used to calculate the earth current.

The fault current split for this analysis has been determined using the Right-of-Way software package [1] (TRALIN and SPLITS computation modules) based on the short circuit fault current contribution from each terminal substation feeding the station transmission lines.

Table 4: Station Ground Grid Impedance, Earth Current, and GPR

Soil Model	Ground Impedance (Ω)	20-Year Horizon Fault Level	
		Earth Current (A)	Ground Potential Rise (V)
Summer	**1.62**	**1728.1**	**2799.5**
Spring	**5.65**	**578.61**	**3269.17**
Winter	**7.75**	**429.65**	**3329.77**

The high and low side single-line-to-ground (SLG) faults used for transmission type stations, assume that all high and low side buses are fully networked. In most cases, the bus with the largest SLG fault magnitude is used for determining GPR and touch and step voltages in the safety analysis study, however, attention must be paid to line faults occurring outside the station. In this case, the absence of significant local generating sources did not warrant such attention.

The system fault data used in this study was provided by Manitoba Hydro. Note the 230 kV fault currents contributed from one of the 115 kV incoming line through the autotransformer banks are not due to any significant generating sources on the 115 kV level of the network but rather currents transferred from the 230 kV network. Consequently, the currents on the 115 kV phases are equal in magnitude and angle and can be considered as pure zero sequence currents for all practical purposes. A portion of the fault current discharged in the substation grid returns to the transformer neutrals where they are diverted by the 115 and 230 kV shield wires.

2.6 Safety Analysis

This section evaluates the station's touch voltages, step voltages and ground potential rise (GPR), ensuring they meet safety under all contingency criteria. The following safety criteria are applied to every design to ensure consistency, and safety throughout the station area. Initially, the insulating surface layer resistivity at the station, when wet, was assumed to be 3,200 Ω-m, a value equal to the resistivity of the sub-surface (native) soil in summer. Therefore the ANSI/IEEE Guide 80 method for the computation of the foot resistance no longer applies because it assumes that the surface covering layer resistivity is significantly larger that the shallow soil layer resistivity. Consequently, the foot resistance must be computed separately based on the actual soil layers. This observation provided a strong incentive to measure the crushed rock resistivity at Herblet Lake Station because it was unlikely that, under such conditions, the station crushed rock layer, when wet, would exhibit a resistivity that is about the same or lower than that of the native soil in summer. Indeed, the measurements confirmed that the resistivity of the wet crushed rock was 28,750 ohm-m. However, a significant portion of the scenarios examined during the study was conducted assuming that the surface layer resistivity exhibits the low resistivity value of 3,200 ohm-m.

A computer model of a foot was chosen so that its ground resistance is about 3 times the surface layer resistivity (more precisely, 284.6 Ω for a 100 Ω -m uniform soil). The foot electrode is a 14.2 cm long, square plate and is equivalent to an 8 cm radius circular IEEE # 80 plate. The thickness of the plate is 1 mm and is buried at a depth of 5 mm. The computed foot resistance in various soil models using the IEEE Guide 80 expression (as computed by the MultiGroundZ safety module) and a more appropriate computer model of the foot and surface soil layers is shown in Table 5. It is quite clear that there is a significant error in the value computed using the Guide 80 expression. The Table gives the maximum tolerable touch voltages for spring, summer and winter conditions, taking into consideration the computed foot resistance.

Table 5: Foot Resistance and Safe Touch Voltages for Seasonal Variations of Top Soil Surface Resistivities

Season	Foot Resistance (ohms)		Top Soil Surface Resistivity (ohm-m)	Safe Touch Voltage (V) Exact Model
	IEEE 80	Exact Model		
Spring	10,950.6	26,700	7,079.5	2238.3
Summer	9,474.0	9,505.5	3,200	897.3
Winter	18,903.8	370,810	128,000	29,075.9

Table 5 gives the maximum tolerable touch and step voltages for spring, summer and winter conditions assuming that the person is standing on the native soil (identified here as the top soil surface resistivity). Table 6 gives the maximum tolerable touch and step voltages for spring and summer and assuming that the person is standing on a 6" surface layer of crushed rock.

Table 6: Station Ground Grid Performance and Safe Touch Voltages with Surface Crushed Rock

Soil Model	Computed Grounding Grid Performance			Safe Touch Voltages (V) Assuming a Surface Layer Resistivity of:	
	Total Earth Current (A)	Ground Grid Impedance (Ω)	Worst Touch Voltage (V)	3.2 kΩ-m	13.5 kΩ-m
Summer	1728.1	1.62	1627.6	897.3	2941.1
Spring	578.6	5.65	2932.3	2238.3	3159.8

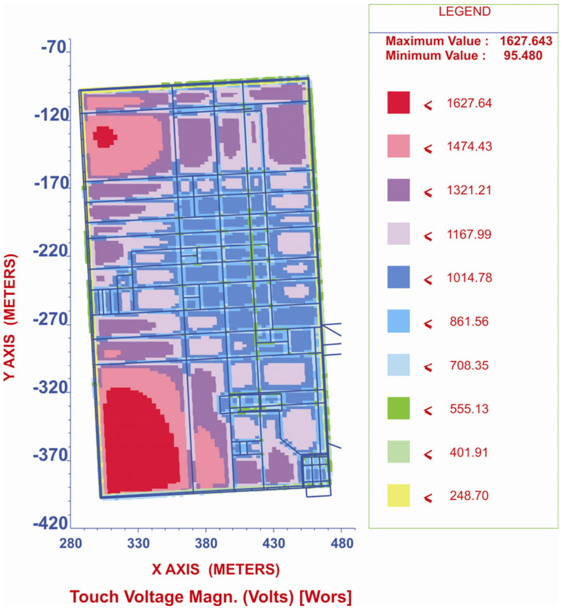

Figure 7: Touch Voltages Distribution during Summer Conditions

Table 6 gives the computed maximum touch voltages as well as the corresponding safe touch voltages that apply to the present station grounding system (as-built).This table corresponds to the 20 Year Horizon 230 kV fault case. This table suggests that in order to have a safe grounding system without any mitigation measures whatsoever, a wet, 6" thick crushed rock layer with a minimum resistivity value of 13,500 ohm-m must exist over the entire station site.

Various design scenarios were studied to ensure that all areas inside the station perimeter fence meet safe touch and step voltages for the ISD and 20 Year Horizon ground fault currents. All scenarios that were investigated correspond to the case where the surface crushed rock layer, when wet, is assumed to have a soil resistivity that is equal to the native soil value and therefore, was not included as an active layer in the safety calculations.

The following main scenarios and several derived scenario variations were examined for the worst case of a 230 kV fault at the station. Note that for Scenarios 1 to 4, the surface layer of crushed rock is assumed to have a resistivity of 3,200 ohm-m when wet.

- Scenario 1: Existing ground grid (including Communication tower site and the 5mx5m remote grid).
    1. Present grid, no mitigation
    2. Present grid, alumoweld shield on the first 5 km of the new 230 kV transmission lines from station
- Scenario 2: Existing ground grid (including Communication tower site) and an enhanced remote grid buried in the large 220 m x 100 m and 10 m deep water pond). Alumoweld shield on the first 5 km of the new 230 kV transmission lines from station
- Scenario 3: Existing ground grid (including Communication tower site and the 5 m x 5 m remote grid) and 5 km of continuous counterpoises along the new 230 kV transmission lines.
- Scenario 4: Enhanced ground grid (including Communication tower site and the 5 m x 5 m remote grid). Various degrees of grid enhancements and reinforcements were analysed. Alumoweld shield wires on the first 5 km of the new 230 kV transmission lines from station.
- Scenario 5: Present grid, no mitigation but with the measured wet crushed rock layer resistivity.

The analysis of Scenario 1 and its derivatives indicated that the station grounding system was not safe. Consequently, significant grid density reinforcement, or remote ground system enhancements, or transmission line tower ground and shield wire material enhancements would be required. The computer model results corresponding to Scenario 2 and its derivatives indicated that the station grounding system was still not safe when the remote grid was buried in the 220 m x 100 m x 10 m water pond. The analysis of Scenario 3 and its derivatives revealed that the station grounding system was still not safe with the addition of 5 km of continuous counterpoises along the new 230 kV transmission lines.

Finally, after it became rather clear that the above various mitigation solutions that avoid adding conductors in the grounding system within the station perimeter loop were not effective, Scenario 4 was examined for various seasonal conditions and fault current level conditions. It then became clear that the addition of a rather large number of ground conductors, are needed to achieve safety requirements. The measurement results of the wet crushed rock surface layer covering the station revealed a value in excess of 28,000 ohm-m, significantly more than the minimum value of about 13,500 ohm-m required in order to avoid any reinforcement of the grounding system.

3. Conclusion

The importance of analysing seasonal soil resistivity variations effects on substation ground grid performance is clearly demonstrated in this study. Furthermore, foot resistance computations using IEEE Guide 80 were shown to be wrong in several cases and an exact method to compute accurate foot resistance was discussed.

The importance of conducting multiple resistivity measurements in order to establish appropriate soil model structures for various climatic conditions was demonstrated. Measuring the resistivity of the surface covering material was shown to be a critical factor in achieving an economical ground grid design and avoiding costly intrusive mitigation measures.

The present station grounding grid design, meets safety requirements for transferred potentials, step voltages and touch voltages based on the measured 28,750 ohm-m wet surface layer of crushed rock that covers the entire station. In fact, the study revealed that a wet surface layer resistivity of crushed rock with a resistivity of 13,500 ohm-m (about half the measured value) is enough to insure all safety requirements.

This study investigated also the hypothetical case of a 3,200 ohm-m wet surface layer of crushed rock and concluded that the present station grounding grid design, will not meet the safe touch voltage limit. Consequently, based on this hypothetical case, reinforcements of the grounding grid and transmission line shield wires and structure ground improvements would be required for present and future fault conditions.

Acknowledgements

The authors gratefully acknowledge Manitoba Hydro for permission to publish this paper and for its continuous technical support. The financial and technical resources provided by Safe Engineering Services & technologies ltd. for this research work are also acknowledged.

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