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Grid-Connected Low-Voltage Power Supply to Equipment on Transmission Line Structures

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***Abstract*—Electrical equipment installed on high-voltage (HV) transmission structures may require low-voltage (LV) electrical supply from the distribution network. For example, cell sites for communication antennas and warning lights are the most common applications in BC Hydro's system. Bringing the LV supply to the HV structures introduces a number of electrical concerns. The first concern is the transfer of ground potential rise (GPR) from the HV system to the LV system during a ground fault on the transmission structure. The second concern is the induction in the LV system due to the proximity to the HV transmission line. In addition, there could be system impacts that require special attention, such as reduction in circuit-to-circuit separation in multiple-circuit corridors, pole fire on the LV wood poles, etc. This paper discusses technical solutions to mitigate the identified concerns and system impacts. Amongst the possible recommendations, addition of appropriately rated isolation transformers to the LV feeder and improving the electrical grounding on the HV transmission structure are shown to be the most effective methods for preventing the transfer of hazardous potentials to the customers connected to the same LV feeder. The proposed isolation circuit has been tested in a HV laboratory to confirm its effectiveness.**

***Index Terms*—GPR transfer, isolated supply, cell site antennas.**

I. Introduction

Due to the limited space in urban areas, cell carriers consider the tall transmission structures as one alternative for installing their telecommunication antennas. For power utilities, this will be a source of secondary revenues to rent their structures to cell carriers. This has been a common practice in BC Hydro and there are a few hundreds of cell site antennas installed on high-voltage (HV) transmission towers within the Lower Mainland area in BC. This installation typically includes a cell site compound installed next to the tower and a few cables running up to the antennas installed on the tower top. A low-voltage (LV) distribution supply is always required to power up the equipment inside the cell site compound. This is typically provided through a single-phase 12.5 kV or 25 kV distribution feeder and a service transformer to bring the voltage down to 120V/240V. A very similar situation exists when warning lights are installed on top of transmission towers near river-crossings for aircraft warning. These lights also require an LV supply which is typically provided through a distribution feeder. Another instance is capacitor stations or switching stations, where no power transformer exists to provide power supply to the station equipment. A distribution feeder is typically used to provide power to these stations.

A typical cell site power supply scheme is shown in Fig. 1. In this figure, the grounding connections are depicted. Based on this connection, the following issues arise:

- When there is a fault on the transmission tower, the ground potential rise (GPR) of the tower foundation is directly transferred to the distribution neutral and possibly phase conductor. This hazardous voltage is then transferred to customer premises, causing equipment damage and/or public safety hazard.
- The proximity of the distribution circuit and the LV wiring to the HV transmission circuit introduced some induced voltage that could exceed the appropriate limits.
- Depending on the location of the distribution feeder and the LV wiring system, the existing circuit-to-circuit separation between adjacent HV transmission lines could be jeopardized, leading to a higher risk of simultaneous outages due to a lightning strike in that location.
- Installation of the cell site compound in populated urban areas can increase/spread the risk of step and touch potential hazards in case of a ground fault on the transmission tower.

The Institute of Electrical and Electronics Engineers (IEEE) published a standard that addresses some of the issues pertaining to cases where communication facilities provide service to electric supply locations [1]. The main purpose of this standard is to protect the communication facilities and to this end, some recommendations are made therein. The use of fiber optic cables between the communication facility and the HV facility can eliminate some of the hazards. This practice, however, is not always possible due to the requirement for coaxial cables for some type of cell sites. There is a recommendation for installing an LV isolation transformer (Figure 1 in [1]) as well as surge arresters to provide some level of protection. This scheme, as will be shown later in this paper, is inadequate for the particular cases where a distribution feeder supplies a load on a HV transmission structure. It will also be shown that the surge arresters are essentially ineffective in blocking the GPR from getting transferred to the distribution system.

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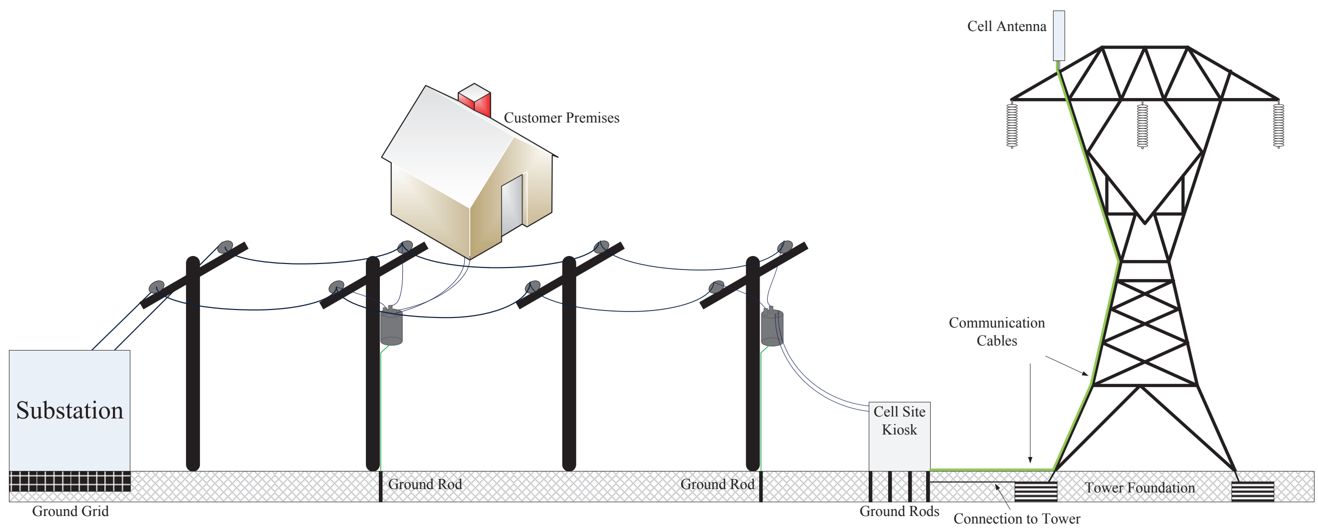

Fig. 1. Typical LV power supply scheme to a cell site compound installed next to a transmission tower.

BC Hydro is not the only utility that allows the installation of cell antennas on the HV towers. Hydro Quebec has previously looked into the related issues and has published the interim results in [2]. A proposal was made in [2] to install an isolation transformer on the source side and remove the bond from the tower to the service transformer. The issue with this scheme is that when the GPR on the tower is higher than the insulation level of the service transformer, the perceived isolation will be compromised and the high GPR will be transferred to the isolation transformer. The isolation transformer will, in turn, fail due to insulation failure and the whole scheme will be ineffective. It is also important to note that most utilities benefit from having shield wires installed on the HV transmission lines. These shield wires help lower the GPR at a particular tower due to the current split factor. To make the shielding effective, it is also crucial to lower the tower grounding impedance below a target value. These two factors effectively lower the GPR at the towers down to relatively small values. In BC Hydro, however, the HV transmission lines are generally not shielded and, therefore, higher GPR values exist. A quick background on why HV transmission lines are not shielded in BC Hydro can be found in [3]. It should be noted that at the time [2] was published, no final decision had been made on the isolation scheme to be used and it was just a proposal. The proposed method in this paper is based on the same general idea of [2], with some important short comings addressed.

To the best of the authors' knowledge, there is not a defined limit in standards for the neutral voltage rise (NVR) in distribution systems during a fault. At BC Hydro, a limit of 10 V has been specified for the steady-state NVR, which can be caused by load unbalance. When there is a ground fault in a distribution feeder, there will be a NVR, for which the authors are not aware of any defined limit. The Canadian Electrical Code Part I C22.1-15 [4], Section 36- 304 specifies that "the ground resistance shall be such that under all soil conditions that exist in practice (e.g., wet, dry, and frozen conditions), the maximum ground fault current conditions shall limit the potential rise of all parts of the station ground grid to 5000 V". This is primarily to protect the communication cables inside the substation. Section 36-308 (5) further specifies that "A line neutral conductor on grounded neutral systems shall be connected to the station ground electrode". To comply with this code, it is important to make sure the transferred GPR to the station grid through the distribution neutral is below 5 kV. This becomes particularly important when the location of the cell site is relatively close to the medium voltage substation, as the station grid may not have been designed to safely carry the fault currents up to the magnitudes that exist in a HV transmission system. Ground faults on unshielded HV transmission towers would usually cause GPR values much higher than 5 kV.

The rest of this paper is organized as follows. In Section II, the proposed mitigation scheme is described to provide effective isolation between the HV and LV systems. Other issues pertaining to the proximity of HV and LV circuits are discussed in Section III. The main findings of this paper are summarized in Section IV.

II. Proposed LV-HV Isolation Method

A. Ground Potential Rise

Historically, BC Hydro has been applying the idea of removing the neutral connection to the transmission tower as a mitigation measure. This is shown in Fig. 2. The standard neutral connection method is also shown for the customer load in Fig. 2. For the cell antenna site, however, the connection to the load-side grounding is removed, with the hope that the service transformer would block the GPR transfer. This is valid only if the GPR is lower than the insulation level of the service transformer. Based on the CSA standard C2.2-06 (Table 9) [5], the 14.4 kV service transformers are classified as 18 kV insulation class. This class of transformer must have

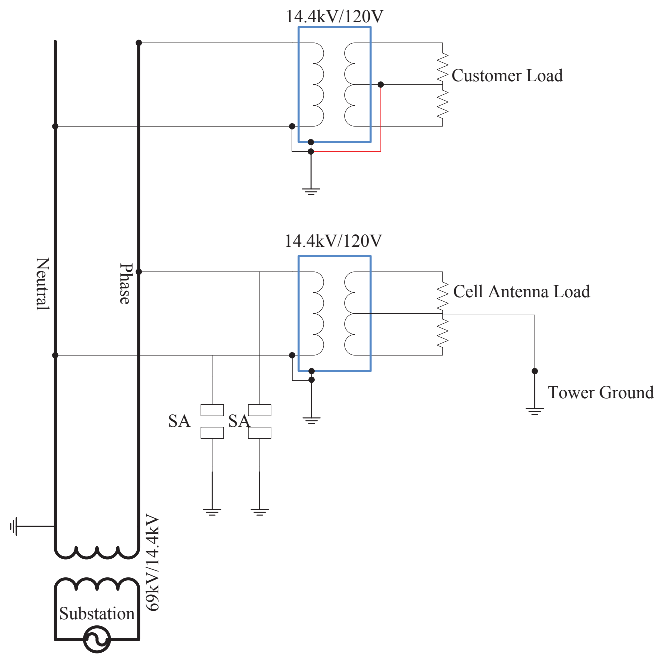

Fig. 2. Historical isolation method used to minimize the risk of GPR transfer from HV to LV system.

a withstand voltage of 40 kV for 1 min between the two windings (one winding energized, the other winding grounded). It is, however, not clear what the maximum withstand voltage would be for the duration of a transmission fault (mostly below 1 sec). If the GPR is higher than 40 kV, it is possible that the transformer fails and the GPR gets transferred to the distribution system. The surge arresters (SA) shown in Fig. 2 are station-class arresters rated at 18 kV, grounded through a couple of ground rods. When the service transformer fails, these SAs will see the high GPR and enter into "conduction mode". This shorted SAs will just become a part of the tower grounding system and, therefore, the overall transferred GPR to the distribution system will still be high.

The transmission lines in BC Hydro are generally not shielded and, therefore, the entire fault current will be injected to the ground through the faulted tower foundation, yielding very high GPR. In order to calculate the GPR at a particular tower, the Thévenin equivalent impedance is first calculated for the tower location (in terms of sequence impedances). This can be obtained from the utilities protection planning base case, which includes the entire system model. In order to account for the future growth of the system, the "ultimate fault levels" are used when calculating the Thévenin impedance. A fall-of-potential and a soil resistivity measurement need to be conducted at the location of the tower under study. The measured tower grounding impedance is then used as the fault impedance in order to calculate the GPR in case of a ground fault.

In order to illustrate the concepts, a test case was built based on a real project. A cell site is installed on top of a 500 kV lattice tower. This tower is a rigid (self-supported) structure with four grillage-type foundations. The cell site compound, located a few meters away from the tower foundations, has its own ground grid, comprised of a few ground rods and a loop of counterpoise wire connecting them all together. There are two counterpoise wires connecting the compound grid to the tower foundations, as shown in Fig. 3.

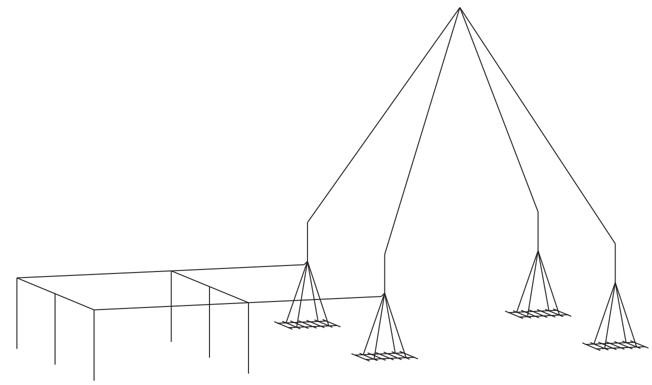

Fig. 3. Typical tower foundation (rigid-tower, grillage foundation), cell site compound ground grid (ground rods and counterpoise wires), and relevant connection between the two.

The distance from the stations is one of the determining factors for the available fault current at a particular structure location. One of the worst cases in terms of GPR would happen when the cell site tower is close to a major substation terminal, which happened to be the case for this project. The ultimate Thévenin impedance at the tower location was estimated as

$$Z_p = Z_n = 0.3 + j5\ \Omega, \quad Z_0 = 0.9 + j8\ \Omega \tag{1}$$

The GPR at the tower is then calculated as

$$\text{GPR} = \frac{Z_g}{(Z_p + Z_n + Z_0)/3 + Z_g}\, V_{\text{ph}} \tag{2}$$

where Z_g is the total grounding impedance at the tower and V_{ph} is the pre-fault phase-to-ground voltage. The grounding impedance Z_g is proportional to the uniform soil resistivity. For this particular foundation, the coefficient that relates grounding resistance to soil resistivity (ρ) was calculated using a commercial grounding software as:

$$Z_g = 0.033\rho \tag{3}$$

Based on the above, the resulting GPR at the tower was calculated for various soil resistivity values, as shown in Fig. 4. As can be seen, expected GPR values are generally beyond the insulation withstand of a distribution service transformer. When the transformer fails, it can be assumed that the distribution conductors will be connected to the tower through the failed transformer. This case is also simulated in the grounding software. The conductor used for distribution neutral is Raven conductor, grounded using a 2.5m rod at every 300m, runs 5 km to the substation, with station ground grid resistance of 0.5 Ω.

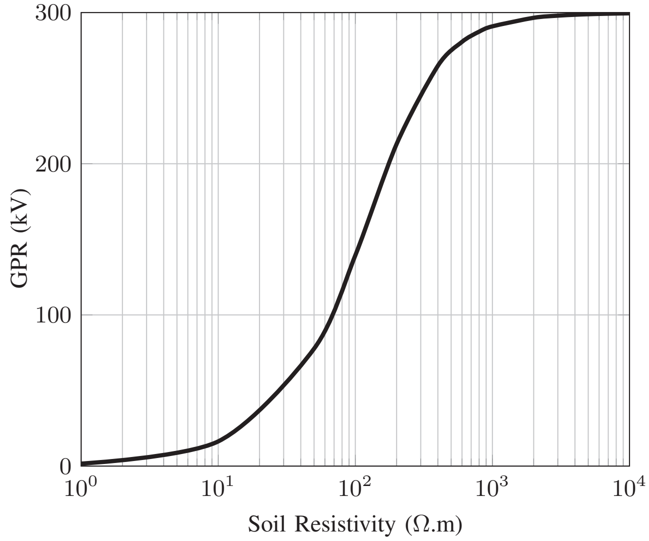

Fig. 4. Tower ground potential rise as a function of local soil resistivity (pre-fault voltage 1.04 pu).

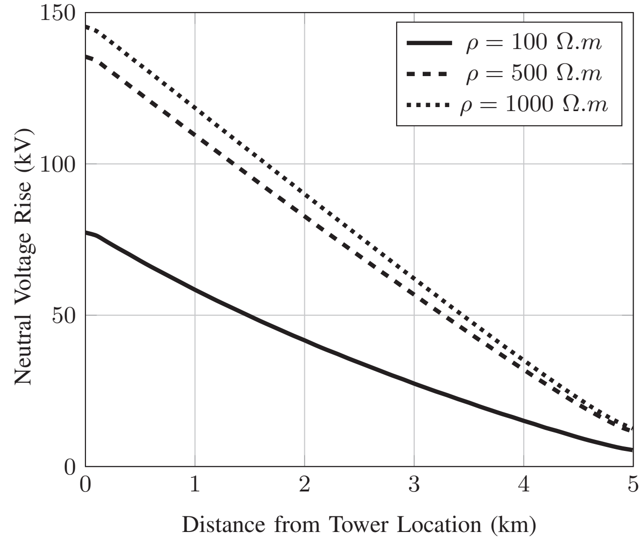

Fig. 5. Voltage profile along the distribution neutral bonded to the transmission tower for various soil resistivity values (5 km to the substation, station grid resistance = 0.5 Ω).

When there is a fault on the transmission tower that causes the supply transformer insulation to fail, the GPR will be distributed along the neutral conductor, all the way back to the substation. Assuming the soil is the same in the entire area the distribution neutral runs through, the voltage profiles shown in Fig. 5 were obtained for various soil resistivity values. The average rate of voltage drop in this figure is 15, 25, and 27 kV/km for soil resistivity values of 100, 500, and 1000 Ω.m, respectively. The higher the soil resistivity, the higher the NVR would be. All the customers fed from this feeder will be exposed to this NVR. In addition, the voltage rise at the distribution substation is higher than 5 kV, thus not meeting the Canadian Electrical Code requirement described in [4] and adopted by BC Hydro.

The station-class SAs shown in Fig. 2 will conduct under the calculated GPR. These SAs are grounded using two ground rods and when conducting, will just act like another grounding point and cannot block the GPR from propagating to the rest of the distribution system. As such, their application has been discontinued for this purpose.

B. Proposed LV-HV Isolation Scheme

In order to address the concerns, the scheme shown in Fig. 6 was proposed. In this scheme, the neutral between the service transformer and the isolation transformer is floating, i.e. it is not connected to ground. When there is a GPR at the tower, the service transformer in series with the isolation transformer will be exposed to the full GPR. The combination of the transformers will increase the voltage withstand of the whole setup. According to CSA standard C2.2-06 [5], each transformer must withstand 40 kV for 1 min. The capacitance of the transformers between primary and secondary windings (each winding shorted) was measured in a high voltage lab for two samples. The results show an average of 900 pF for the service transformer and 1400 pF for the isolation transformer. Therefore, the voltage distribution between the series combination will not be even. The series combination of the transformers was tested in a high voltage lab to understand the withstand voltage. The equivalent circuit of the test setup is shown in Fig. 7. The connections between T1 and T2 are floating. The voltage to ground V_2 can be theoretically calculated using the measured capacitances for T1 and T2. Assuming that the capacitance of the voltage dividers is negligible:

$$V_2 = \frac{C_1}{C_1 + C_2} V_1 \tag{4}$$

where C_1 and C_2 are the capacitances of T1 and T2, respectively. Using the measured values provided above for C_1 and C_2, V_2 would be around 40% of V_1, which means more voltage stress would be imposed on T1.

Two different sets were tested in the lab. A resonant test system (RTS) was utilized to perform the withstand test. The first set failed at 125 kV-RMS, and the second set failed at 150 kV-RMS. Both failures were external, across the bushings of the isolation transformer, as shown in Fig. 8. The pre-test evaluations such as partial discharge tests, induced voltage tests, and capacitance measurements did not reveal a great difference between the two transformer sets. The difference between the withstand voltage of two sets could be associated with small manufacturing differences between them.

In reality, the source side of the transformers is energized at 14.4 kV. In addition, the aging effect would reduce the voltage withstand of the transformers. With these factors in mind, it was decided to adopt 100 kV as the voltage withstand of the transformer set. If the tower fault imposes a voltage stress across the series transformers (measured between the tower foundation GPR and the GPR picked up by the isolation transformer ground rod) is within 100 kV, then no further action is required. Otherwise, additional grounding needs to be installed at the transmission tower to lower the GPR below 100 kV.

In addition to the transformers' voltage withstand, it is important to calculate the GPR acquired by the neutral at the isolation transformer location. Note that there is no direct electrical connection between the ground rod at the isolation transformer location and the ground rod at the service transformer location shown in Fig. 6. The ground rod at the service transformer assumes the same GPR as the tower due to its direct connection, but the ground rod at the isolation transformer location only acquires the voltage transferred through the soil. Let us assume the service transformer is located 6 m away from the closest tower leg. The distance between the isolation and service transformers poles and the soil resistivity would then determine the magnitude of the transferred GPR to the system neutral. The maximum NVR was calculated for various soil resistivity and separation between the transformers. The results are presented in Fig. 9. Note that NVR drops along the neutral wire back to the substation, as shown in Fig. 5. The transferred voltage is higher at around 100-200 Ω.m range, and drops at higher or lower levels. The transferred voltage increases as the distance between the two transformer poles decreases. Based on the calculations on many distribution feeders, the NVR could reach values up to 7 kV due to a SLG fault on the 25 kV feeder (worst case). Therefore, it was deemed acceptable to limit the maximum GPR transfer to 5 kV to make sure the transmission fault does not put the distribution under a higher stress than it would experience due to a fault on the feeder itself.

The proposed isolation scheme is based on an overhead design. When existing/new underground cables need to be tapped into to feed a new site, it is important to make sure the cables have sufficient withstand for the expected GPR due to a fault at the transmission towers. The cable jackets are usually thin and have a low withstand voltage. A puncture through the jacket will leave the sheath connected to the ground, which exposes it to the high GPR originating from the HV tower fault. Therefore, the jacket withstand voltage will be used to determine the minimum separation requirement from the tower. The GPR profiles for various soil resistivity conditions were calculated for a ground fault at the 500 kV tower. The profile starts from the edge of one tower leg and runs for over a 100 m radial distance. Figure 10 shows the calculated GPR profiles. For instance, if the soil resistivity is 100 Ω.m and the cable withstand voltage is 20 kV, the minimum separation distance from the tower leg to where the cable is buried would be 25 m.

In addition to the solution proposed in Fig. 6, other solutions have been pursued in BC Hydro to mitigate the GPR transfer issue. One solution was to utilize the scheme shown in Fig. 2 with a specially designed transformer that would have enough insulation to withstand the maximum expected GPR. The other solution was to use a scheme similar to what is shown in Fig. 6, but use more transformers connected in series to increase the withstand voltage of the combination. Capacitors

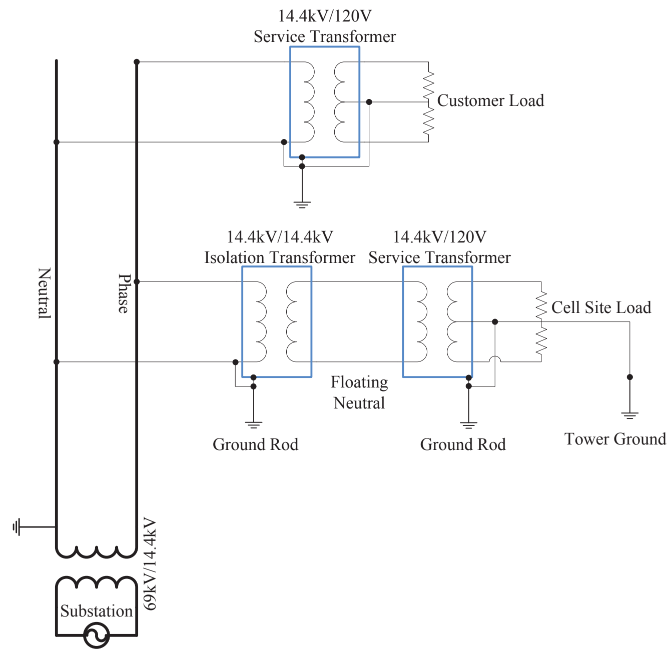

Fig. 6. Proposed LV supply circuit to minimize the risk of GPR transfer from HV system to LV system.

were installed in parallel to the transformers to make sure the voltage stress is distributed evenly between the units. Both these solutions have been proven to be more costly in terms of new investments and/or maintenance, but may still be pursued under certain circumstances.

III. Other Considerations

A. Electric and Magnetic Coupling

When a conductor is placed in parallel with transmission lines, two types of induced voltage will appear on this exposed conductor: inductive and capacitive. The first one is mostly driven by the current flow in the transmission line, whereas the second effect is mostly driven by the transmission line voltage. Based on current BC Hydro standards, the voltage increase due to inductive coupling on LV wiring systems must be limited to 5% of the rated voltage. This would be 6 V for a 120 V wiring system. This limit would prevent any damage to the equipment connect to the LV system due to excessive induced voltage and ensures power quality requirements are not violated.

When distribution feeders are out of service (disconnected from the substation), the service transformers remain connected to the feeder. There could be some unloaded or lightly loaded transformers on the de-energized feeder. When this feeder is energized through capacitive coupling with an energized HV transmission line, there is a chance of Ferro-resonance in the LV feeder that could damage the transformers and customer equipment. Details of this analysis are outside the scope of this paper. Based on current BC Hydro standards, the capacitive coupling voltage must be limited to 80% of the

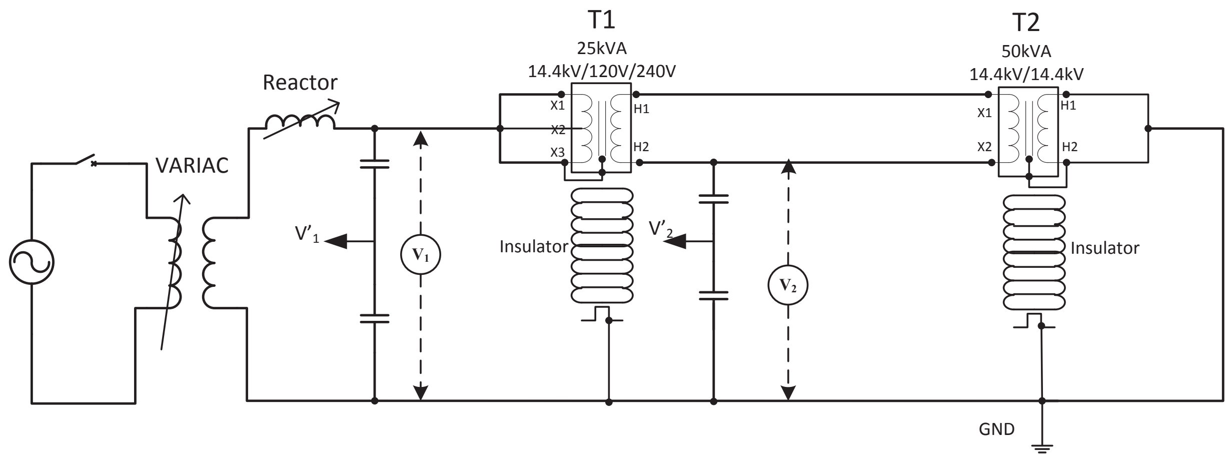

Fig. 7. Equivalent circuit of the voltage withstand test at a high-voltage lab using a resonant test system.

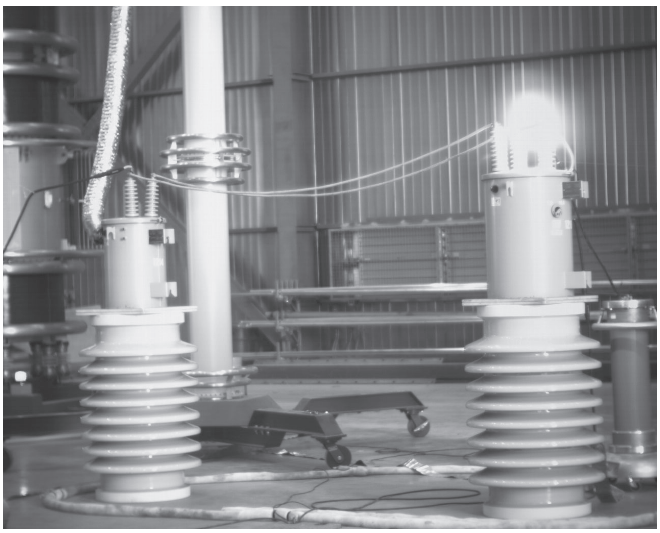

Fig. 8. Voltage withstand test at a high-voltage lab using a resonant test system. The left hand-side transformer is a 14.4 kV/120 V, 25 kVA service transformer, the right hand-side transformer is a 14.4 kV/14.4 kV, 50 kVA isolation transformer. The external flashover across the bushings of the isolation transformer is visible (at 125 kV-RMS).

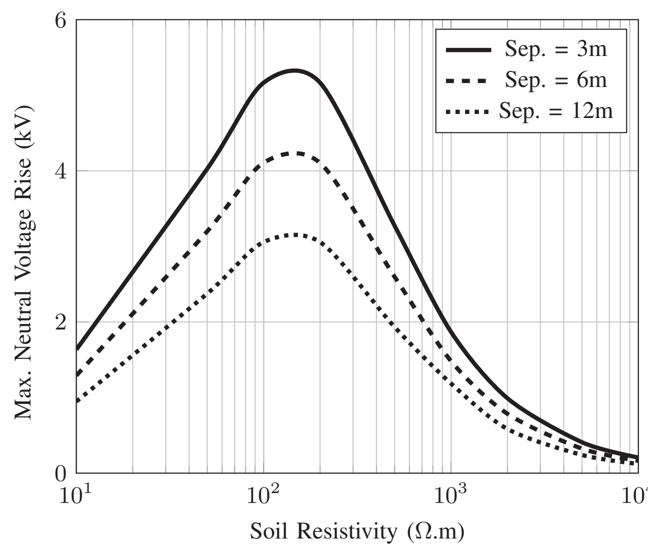

Fig. 9. Maximum voltage rise on the distribution neutral transferred through the soil to the isolation transformer ground rod (connected to the multi-grounded neutral) for various separation distances between the isolation and service transformers poles (5 km to the substation, station grid resistance = 0.5 Ω).

rated voltage to minimize the risk of Ferro-resonance. This would be 11.5 kV for a 25 kV feeder.

Tall wood poles installed under 500 kV transmission lines will cause very high space potentials on the pole top. This excessive space potential can likely cause pole fires if proper bonding is not applied. Based on some empirical data, a limit of 100 kV was suggested in [6] for the unperturbed space potential to start pole fires. This limit is applied at BC Hydro as a criterion to determine the location of the wood poles within the ROW of extra HV transmission lines. When wet wood is exposed to a high space potential, arcing may develop especially around pole hardware (dry band arcing). This arcing would eventually lead to further drying of the wood, increasing resistance, localized heating, and burning. Proper bonding and grounding is required to avoid these concerns.

High electric field under 500 kV lines can be a source of startle shocks for workers aloft. When working from an insulated bucket truck, workers coming in contact with grounded objects will experience startle shocks, which could cause them lose their balance and suffer secondary effects such as falling or inadvertent movements that would initiate undesired outcomes (letting go of tools, reaching to energized conductors, etc). A limit of 10 kV/m is applied by BC Hydro in such cases to make sure the workers' body current, when touching a grounded object, will not exceed 1-5 mA (limit for startle shocks or perception threshold [7]).

B. Circuit-to-Circuit Separation

The lightning-initiated simultaneous outage of transmission lines sharing the same corridor can be a source of a large

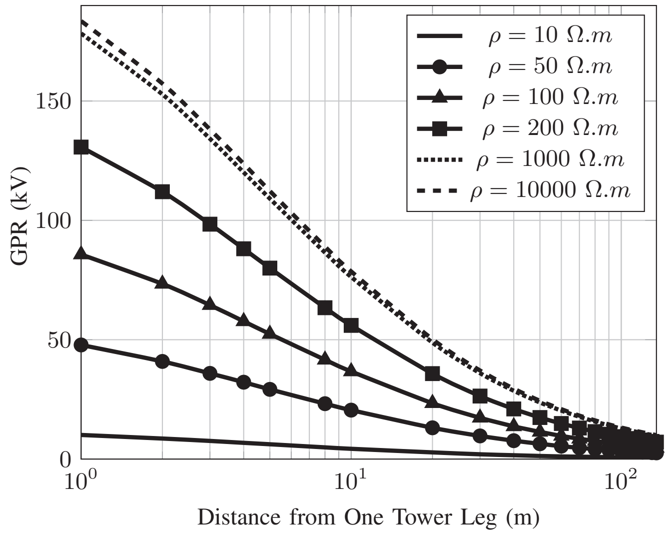

Fig. 10. GPR profiles calculated at various distances from one tower leg for various soil resistivity conditions.

disturbance to power systems. This phenomenon occurs once lightning strikes one circuit and, via an arc established through the soil, breaching the gap between the two circuits and causes a back-flashover on the neighboring circuit. The closer the neighboring structures, the higher the probability of a simultaneous outage. This is a particular concern for BC Hydro transmission lines that are generally not shielded. Other factors also play an important role in determining the number of expected simultaneous outages: ground flash density, local soil resistivity, and tower grounding resistance.

When lightning strikes a line, the current is discharged in the ground via the structure footing. The current discharge would cause the soil to ionize. There have been experimental and theoretical studies to describe the soil ionization phenomenon. The theory states that the equivalent grounding impedance of the grounding system (under soil ionization) depends on the magnitude of the injected current and soil type. Large impulse current magnitudes create a low-resistance "ionized" zone around the electrode, increasing its effective dimensions [8], [9]. The physical phenomenon has been best described by the ionization of the air voids in the soil [10], [11].

When an LV feeder is installed within the ROW of multiple transmission lines, crossing the ROW to get to a particular structure, there is a chance that the existing separation between the structures of adjacent circuits would be compromised. Therefore, it must be considered when designing the route of the LV feeder not to reduce the existing separation between the structures. Other metallic objects that could reduce the in-ground separation between adjacent circuits are fences, pipelines, railways, and counterpoise wires.

IV. Conclusion

Low-voltage (LV) electric supply lines fed from the distribution network are connected to power equipment installed on high-voltage (HV) transmission structures, for example, to power cell antennas. The issues pertaining to the proximity of LV feeders to HV structures were discussed in this paper. An isolation scheme was proposed to minimize the possibility of the hazardous potentials transferred from the HV system to the LV system due to a ground fault on the HV transmission structure. The proposed circuit was tested in a HV lab in order to quantify its withstand voltage. Considering the test results and the equipment ratings, it was decided to use 100 kV as the maximum withstand voltage for the proposed isolation scheme. If the calculated GPR at the HV structure exceeds 100 kV, additional grounding will need to be installed to lower the GPR below the limit. Other issues such as inductive and capacitive coupling need to be considered when designing LV feeders near HV lines. A lightning strike to a transmission line could initiate a simultaneous outage of the parallel transmission lines sharing the same corridor. The separation distance between the adjacent structures plays an important role in the frequency of such simultaneous outages. The LV feeder installation should not reduce the existing circuit-to-circuit separation between adjacent structures of different HV lines.

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