Analysis and Mitigation of Induced Voltages on Substation Control Cables

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Abstract: Substation control cables are susceptible to induced voltages during high frequency transients. Typical practice of shielding and grounding of control cables in substations minimizes the induced voltages on these cables. However, occasionally, these voltages may be at a level that causes failures of sensitive electronic equipment such as digital relays, digital meters, etc. The impact of such failures on system reliability and security can be substantial and unacceptable. The paper presents a methodology for the assessment of the high frequency induced voltages, a testing procedure to assess the severity of the problem, and a summary of the factors affecting these overvoltages.

1. Introduction

Substation control cables are subject to induced voltages during high frequency transients, arising from disconnect switching operations or faults. Control cables are by necessity placed in proximity to substation bus-work and grounding systems. During transients, large currents can flow in the buses and ground electrodes. These currents can induce overvoltages to the control cables by two mechanisms: (a) by magnetic induction via the mutual coupling among control cables buses and ground electrodes, and (b) by conduction or voltage transfer via the grounding system and earth.

The induced/transferred voltages may damage equipment connected to control cables such as digital relays, event recorders, communication devices, etc. With the recent proliferation of digital instrumentation, the effects of induced voltages are becoming more critical. Although, typical practice of shielding and grounding of control cables in substations minimizes the induced voltages on these cables, failures of sensitive electronic equipment are still possible. The impact of such failures on system reliability and security is substantial and unacceptable.

Figure 1 illustrates a typical situation in a substation. It shows a section of the bus-work, the substation ground mat, and a control circuit. One end of the control circuit is grounded while the other end is not. Consider the voltage at the ungrounded end of the control circuit. This voltage consists of two components: (a) differential mode voltage, developed across the terminals of the control circuit (V_{DM}), and (b) common mode voltage, developed between each terminal and ground (V_{CM}). Under normal operating conditions, these voltages are negligible. However, under transient conditions, they may be substantial. During a transient, large asymmetrical currents may flow through the bus conductors. Due to the current asymmetry large currents may be also flow in the grounding system causing non-uniform ground potential rise. Both bus and ground electrode currents couple into the control circuit via the mutual inductance between bus conductors, ground electrodes and control cables. Since the mutual inductances are generally different, unequal voltages will be induced on each control circuit conductor, resulting in both common and differential mode voltage components at the ungrounded control circuit end. Furthermore, an additional common mode voltage component will be generated due to the ground potential difference at the two ends of the control cable.

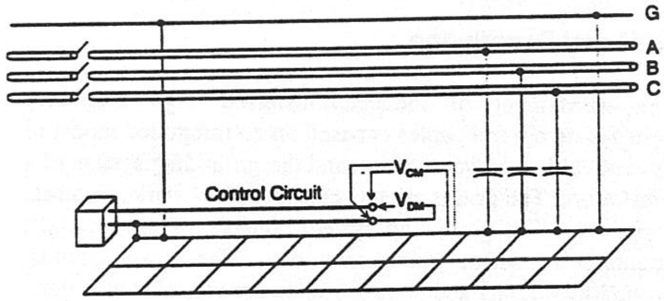

Figure 1. Illustration of the Problem Under Investigation

This paper presents a methodology for the assessment of the high frequency induced voltages, a testing procedure to assess the severity of the problem, and a summary of the factors affecting these overvoltages. The methodology for the assessment of induced/transferred high frequency voltages on control cables is based on an integrated model of control cables, power circuits (bus work, switches, lines, etc.) and the grounding conductors of a substation grounding system. The model is used in a time domain algorithm that provides the net voltage on control cables (induced and transferred via the grounding system). This information is very useful in assessing the vulnerability of the system to these voltages. The paper presents the integrated model and the time domain simulation method. The testing procedure consists of measurements of induced voltages on control cables resulting from circulating currents in the grounding system of the substation via a PC controlled testing device, the Smart Ground Multimeter [1]. This meter injects a randomly alternating current into two points of the substation grounding system and measures the induced voltages on any control cable. The byproduct of this measurement is the extraction of the mutual impedance between control cables and substation ground. This value is then compared with the calculated mutual impedances from the integrated model. Thus the measurements serve as a model validation tool.

The proposed method has been applied in one substation of a US-mid-western electric utility. The substation has repeatedly experienced relay failures due to transients induced on the control cables. The results of the testing, model construction and assessment of the problem are reported in this paper. The results indicate that the mutual coupling among unshielded control cables, ground conductors and bus work is relatively high. This causes relatively high voltage transients during switching that last a very short time. Simulations indicate that shielded cables do not eliminate these voltages all together, but they reduce them considerably to within acceptable limits. Routing of control cables also affects the total transferred voltages. The computer model provides a quantitative analysis of these phenomena.

2. Model Description

The assessment of induced/transferred high frequency voltages on control cables is based on an integrated model of control cables, power circuits, and the grounding system of a substation. The power circuits consist of bus work, switches, lines, etc. The grounding system consists of ground rods, counterpoise wires, ground mats etc. The power circuits, grounding circuits and control cables are modeled as a three dimensional system of metallic conductors, buried or above earth. This set of conductors is analyzed using finite element methods. An example conductor arrangement illustrating the analysis methodology is shown in Figure 2. It consists of two ground electrodes (directly buried in soil) and one overhead conductor, at arbitrary locations and orientations. Each conductor is segmented into a set of short segments. Consider two such segments k and j. Assume a unit step current is flowing in segment k. This current induces voltage on every conductor segment of the system. If the conductor segment k belongs to a buried electrode, electric current can also flow from the surface of the segment into earth. This earth current transfers voltage (by conduction) to every buried segment of the system.

Figure 4a illustrates a typical waveform of the average induced voltage on conductor segment j due to a unit step electric current through conductor segment k. Similarly, Figure 4b illustrates a typical waveform of the average transferred voltage to a conductor segment due to a unit step electric current flowing from the surface of the conductor segment k into earth. The step responses of Figure 4 are called Voltage Distribution Functions (VDFs) because they provide the average voltage of a given conductor segment due to a specific unit step current source. The exact form of the VDFs depends on soil resistivity and permittivity, conductor segment dimensions, orientation, etc.

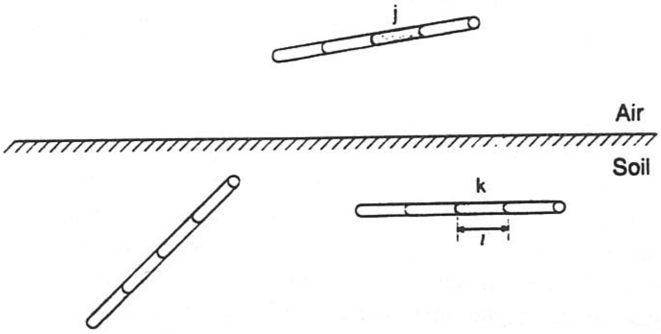

Figure 2. Conductor Segmentation

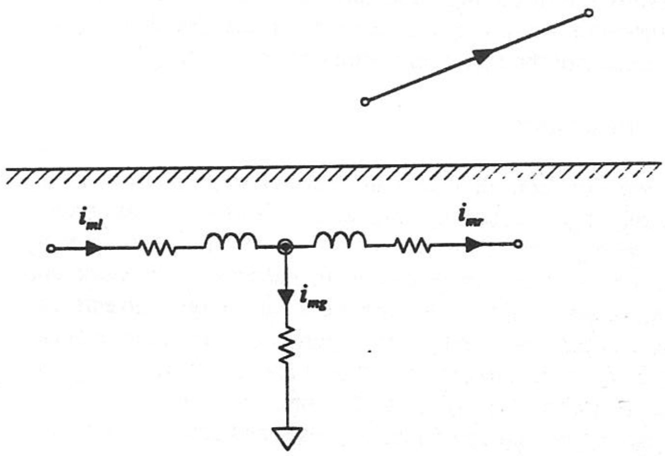

Figure 3. Illustration of Electrical Model of a Ground Conductor Segment and Overhead Conductor Section

Note that the general form of the VDFs exhibits a time delay τ_1, and a settling time τ_2-τ_1. The constant value, to which the VDF settles, is zero if there is no conducting medium between the two conductor elements, and nonzero if there is conducting medium (soil) between the two conductor segments.

Once the VDFs have been computed for any pair of conductor segments, system theory procedures are used for the analysis of voltages and currents in a grounding system due to an arbitrary excitation. For example, the average voltage on segment k is obtained by superposition of the contributions from the currents of all segments.

The above-described model considers the effects of electromagnetic wave propagation through the soil. In addition, electromagnetic waves propagate through the ground conductors themselves.

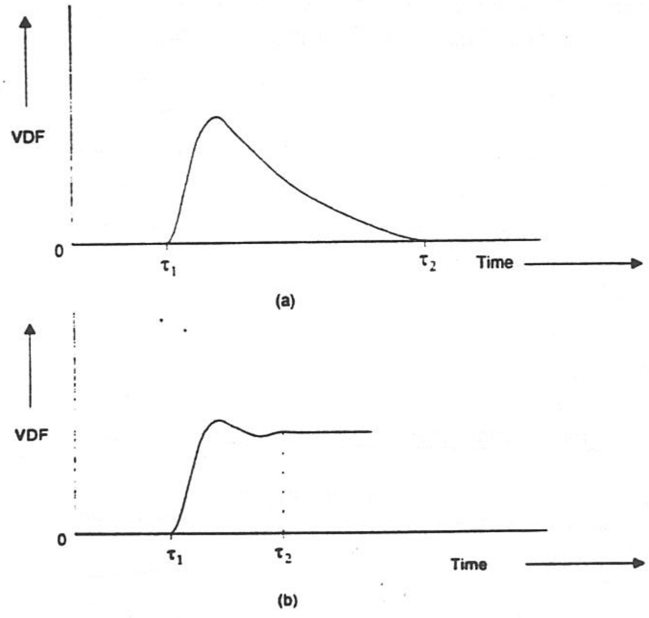

Figure 4. Typical Voltage Distribution Functions
(a) No conductive path between conductor segments
(b) Existence of a conductive path (i.e. soil)

In order to account this effect, each conductor segment is modeled as a transmission line with certain parameters. The mutual inductance between two conductor segments of arbitrary orientation is computed with appropriate utilization of the Neumann integral [3], N, given below.

$$N = pB'\log\frac{Bb+B'b}{Ba+B'a} - pA'\log\frac{Ab+A'b}{Aa+A'a} + Pb'\log\frac{bB+b'B}{bA+b'A} - Pa'\log\frac{aB+a'B}{aA+a'A} - \frac{Pp\Omega}{\tan e}$$

$$= 2pB'\tanh^{-1}\frac{ab}{aB+Bb} - 2pA'\tanh^{-1}\frac{ab}{aA+Ab} + 2Pb'\tanh^{-1}\frac{AB}{Ab+bB} - 2Pa'\tanh^{-1}\frac{AB}{Aa+aB} - \frac{Pp\Omega}{\tan e}$$

where AB, ab are arbitrarily oriented segments. and A'B', a'b' are the projections of AB and ab onto each other. Pp is the common perpendicular segment to ab and AB. Ω is the solid angle subtended at B by a parallelogram abcd where bc is parallel and equal to AB. Finally. e is the angle between AB and ab.

3. Example Results

The methodology described in this paper was applied to a substation of a utility in the mid-west of the United States. The following steps were performed. First. the soil resistivity was measured as well as the mutual impedance of control cables to the grounding mat of the substation. Then. using the measurement. a simplified model was constructed using the measured parameters. The model was extended to study the effect of design parameters, for example the use of shielded control cables to control the induced/transferred voltages. The results are reported here.

Fisrt, soil resistivity measurements were performed in an area adjacent to the substation. Three sets of measurements were taken with the Smart Ground Multimeter [1]. Specifically, one set of measurements was taken by placing nine probes in a straight line with separation distance of 10 feet. Another set of measurements was taken with separation distance 20 feet and another one with separation distance 40 feet. At the largest separation distance. the probes cover a length of 320 feet.

The soil resistivity from all these measurements was extracted and reported in Figure 5. Note that the expected value of the soil resistivity is 18.6 ohm.meter to a depth of 221.6 feet and 12.8 ohm.meter below 221.6 feet. Note also high confidence for the upper soil resistivity and very little confidence for the lower soil resistivity.

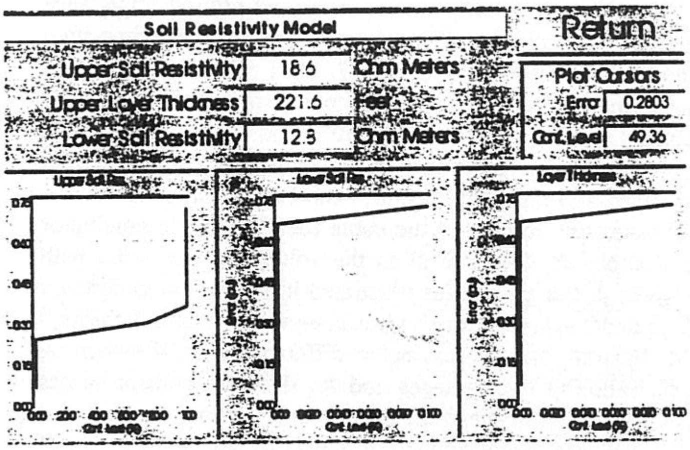

Figure 5. Measured Soil Resistivity Near the Example Substation

Next, the mutual impedance of a selected control cable to the grounding system was measured. The selected control cable is connected to a current transformer at the end of a bus run in the substation. The control circuit is routed via the cable trench that runs for the entire length of the bus and terminates at the control house. The length of the control circuit was approximately 340 feet.

The measurements results are illustrated in Figure 6. Note that only probe 1Y was used. Therefore only the upper left window presents useful data. Note that at 60 Hz the mutual impedance is .01046 ohms with a phase angle 58.42 degrees for the entire 340 feet length. From this value, the following parameters per unit length can be extracted. The mutual inductance at 60 Hz is 0.22 microhenries per meter. The resistive coupling is 53 microohms per meter.

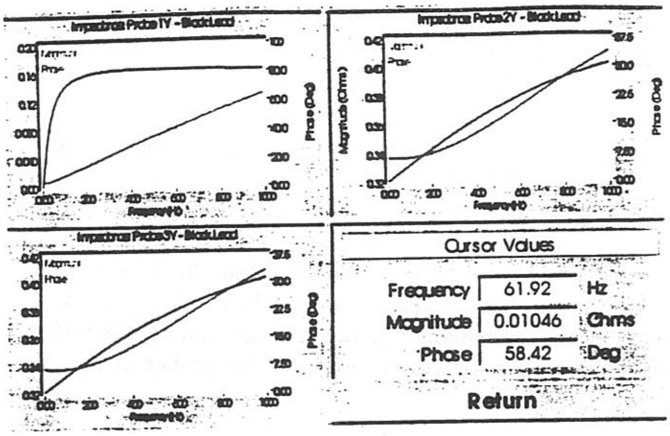

Figure 6. Measured Mutual Impedance Between a Control Circuit and the Grounding System of the Example Substation

Next, a simplified model of the substation grounding system, control circuit and bus work was constructed using parameters consistent with the measured ground impedance and soil resistivities. The pictorial view of the simplified model is illustrated in Figure 7. This model was used to perform parametric studies of total transferred voltage to control circuits (induced, capacitive and conductive transfer voltage) under lightning or switching operations. Both shielded and unshielded control cables were considered. For all cases the voltage of the cable (between cable conductor and cable shield) as well as the voltage of the cable with respect to the ground (as illustrated in Figure 7 and denoted V_{DM} and V_{CM} respectively) was computed. Figures 8 through 14 illustrate typical results for different cases of switching and lightning overvoltages and for different control cables (shielded and unshielded). Each figure provides the voltages V_{DM} and V_{CM} waveforms for the specific case. A summary of the results is given in Table 1. The results indicate that using unshielded cables the total transferred voltage may be excessive. Use of shielded cable can reduce these voltages several times.

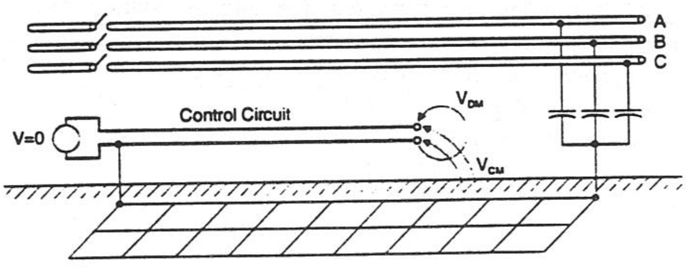

Figure 7. Illustration of the Example System Model

Table 1. Summary of Computed Total Voltage to Control Cable (All Figures in Volts)

	Unshielded Cable	Shielded Cable
Lightning, Close to Ground Conductor	780	195
Lightning, 15 Feet from Nearest Ground Conductor	660	92
Switching, Close to Ground Conductor	3,910	1,140
Switching, 15 Feet from Nearest Ground Conductor	6,870	13

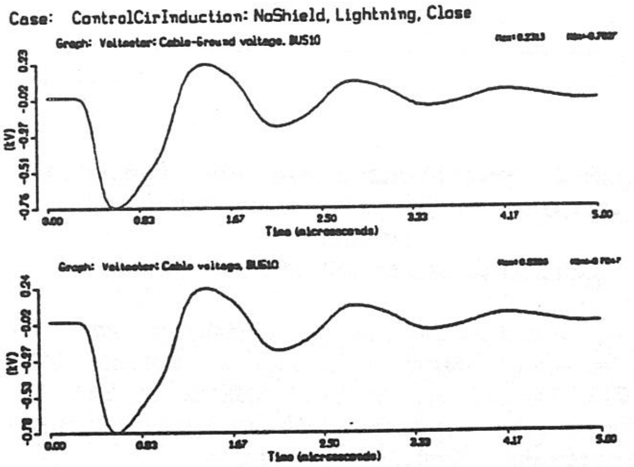

Figure 8. Computed Total Transferred Voltage (Inductive, Capacitive, Conductive) to an Unshielded Control Cable Near a Ground Conductor During a Direct Lightning Hit of 20 kA. Example Substation.

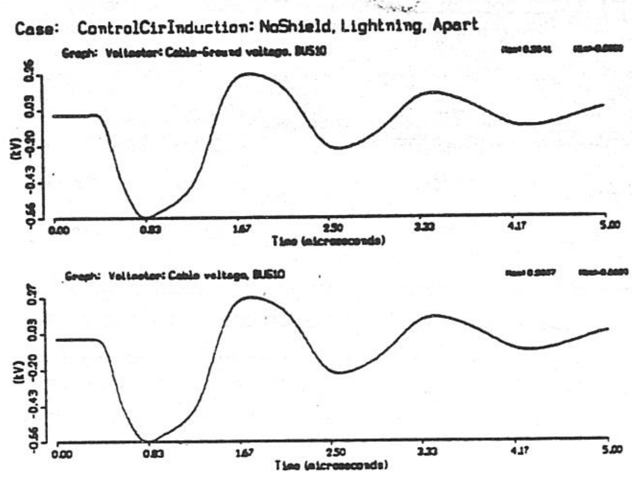

Figure 9. Computed Total Transferred Voltage (Inductive, Capacitive, Conductive) to an Unshielded Control Cable 15 Feet Away from Ground Conductor During a Direct Lightning Hit of 20 kA. Example Substation.

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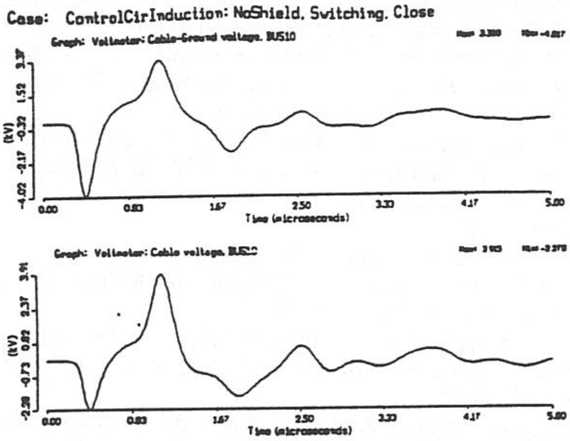

Figure 10. Computed Total Transferred Voltage (Inductive, Capacitive, Conductive) to an Unshielded Control Cable Near a Ground Conductor During a Bus Switching. Example Substation.

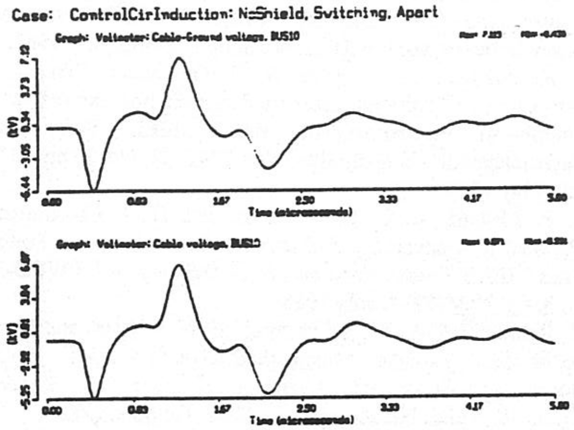

Figure 11. Computed Total Transferred Voltage (Inductive, Capacitive, Conductive) to an Unshielded Control Cable 15 Feet Away From a Ground Conductor During a Bus Switching. Example Substation.

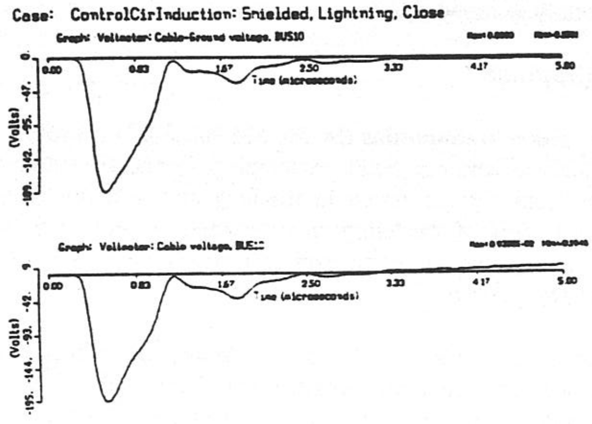

Figure 12. Computed Total Transferred Voltage (Inductive, Capacitive, Conductive) to a Shielded Control Cable Near a Ground Conductor During a Direct Lightning Hit of 20 kA. Example Substation.

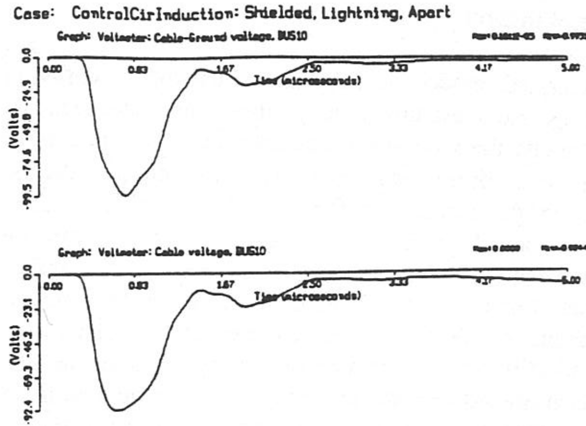

Figure 13. Computed Total Transferred Voltage (Inductive, Capacitive, Conductive) to a Shielded Control Cable 15 Feet Away from Ground Conductor During a Direct Lightning Hit of 20 kA. Example Substation.

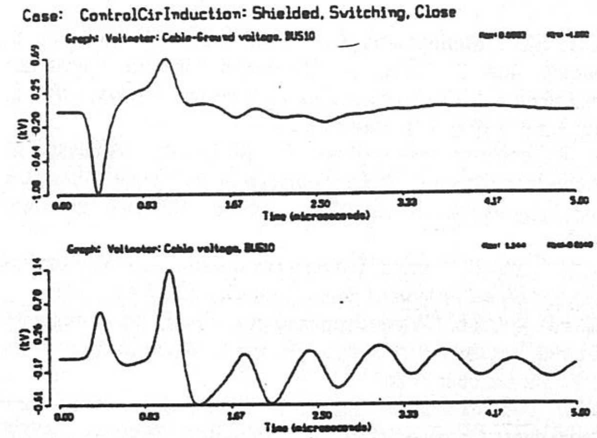

Figure 14. Computed Total Transferred Voltage (Inductive, Capacitive, Conductive) to a Shielded Control Cable Near a Ground Conductor During a Bus Switching. Example Substation.

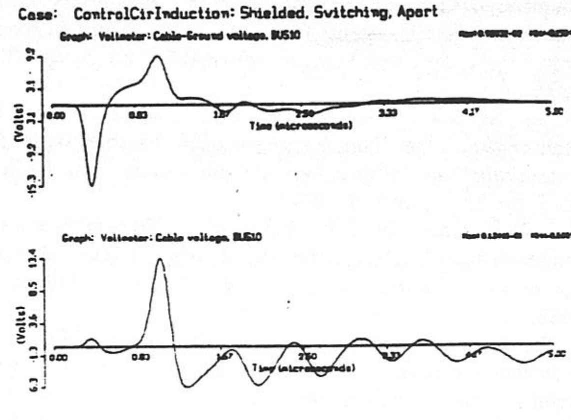

Figure 15. Computed Total Transferred Voltage (Inductive, Capacitive, Conductive) to a Shielded Control Cable 15 Feet Away From a Ground Conductor During a Bus Switching. Example Substation.

4. Conclusions

An integrated model of substation bus-work, substation grounding, and substation control cables was presented. The model can be used to predict induced/transferred voltages to control cables during switching and/or lightning transients. Specific model parameters, for example mutual inductance between control cable and ground conductors, can be measured with the Smart Ground Multimeter and therefore this measurement can be used to validate the model. Assessment of level of induced/transferred voltages to communications circuits can be performed via a testing and simulation procedure. This procedure has been applied to an example substation. The results are presented in this paper. Via simulations, it is shown that use of shielded control cables can substantially reduces the induced/transferred voltages to control cables.

5. References

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