ORNL/TM-2019/1143

High-Voltage Modeling and Testing of Transformer, Line Interface Devices, and Bulk System Components Under Electromagnetic Pulse, Geomagnetic Disturbance, and other Abnormal Transients

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March 18, 2019

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OAK RIDGE NATIONAL LABORATORY
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Electrical and Electronics Research Division

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FY18 - Final Report for the Project Number GM0222 - Grid Modernization Laboratory Consortium (GMLC)

March 18, 2019

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managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

Abstract

This project aims at quantitatively analyzing possible knowledge gaps related to the risk of Electromagnetic Pulse (EMP) impact on high-voltage, power transformers (transmission-class), that represent the most critical power grid assets.

In relation to the electric infrastructure, some past studies indicate that the grid is overall fairly robust and resilient against most EMP threats. This assessment stems, in part, from estimates of the peak voltage that can be induced on a transmission power line for a nominal EMP fast-transient, compared with the typically very high basic insulation level that is featured by the high-voltage infrastructure. The project provides additional insight toward a more comprehensive risk evaluation of the grid EMP and Geomagnetic Disturbances (GMD) vulnerabilities.

This work is aligned with the U.S. Dept. of Energy current research thrust in support of the development of a highly secure and resilient power infrastructure. Project milestones have been devised to address the fundamental technical issues in support of protection of large power transformer against EMP threats.

More specifically, this project included parallel research tasks focused on the following topics:

- Analysis of EMP-induced, fast-transient, current and voltages on a variety of power line configurations and EMP impact scenarios
- Detailed characterization of EMP damage potential due to the voltage surge, from the impact on the power line, to the transformer windings.
- GMD and EMP slow transients and impact from harmonics generation and reactive power flow on a complex grid layout.
- Identification of risk mitigation paths, with emphasis on GIC damage prevention for large power transformers, and on impact protection options from a grid stability perspective.

EXECUTIVE SUMMARY

Scope. The project focused on the threats originating from High-Altitude EMP (HEMP) or Geomagnetic Disturbance (GMD) events that can impact large power transformers that are part of the critical transmission line infrastructure. More specifically, the focus of this analysis is on the power line connecting to the transformers (both primary and secondary), the arresters, bushing and insulators, and the internal winding structure.

The transmission line infrastructure includes other potentially vulnerable components (such as sensors, control and communication electronics, and low-voltage transformer support equipment for cooling and oil circulation) but the impact on these components is outside the scope of this project.

Threat Analysis. The threats that have been considered are classified in two main categories:

i) Fast transients originating from impact of the HEMP waveform in its early times (typically referred to as E1/E2)

ii) Slow transients related to the E3 component of the HEMP and to GMDs.

Fast Transients. The impact an EMP fast transients is mainly related to the generation of voltage surges on the line conductors and that can, in turn, propagate to the transformer. This analysis considers both the determination of the voltage waveshape on the line termination as well as the conditions that may lead to its further propagation, past the arrester, through the bushing and in the winding.

Slow Transients. The consequences of the slower transients are limited to the possibility of generating geomagnetic induced currents (GICs) on a long stretch of a transmission line that are connected to a wye-configured transformer, or to an autotransformer. In these conditions there is the possibility that the GIC drives the transformer magnetic core to saturation, that may lead to a large generation of harmonics and to thermal damage of the transformer internal structure.

This project focuses on the assessment of possible consequences of a large harmonics flow, with potential impact on tripping protections of reactive compensation units, and ultimately to grid instability and voltage collapse. It is also considering the ultimate mitigation option, the installation of GIC capacitive blocking, and analyzing issues related to its grid-wide implementation.

Results - E1. From the analysis of E1 vulnerabilities based on the IEC-HEMP model [IEC, 1986], it can be concluded that power line voltage surges with peak above the line basic insulation level (BIL) are possible. This issue is more relevant for nominal voltages on the lower end of the transmission line range.

For E1-induced transient waveforms faster than the typical lightning time scale, a concern exists related to large voltage residuals occurring on a transmission line termination, before arresters are effective in clamping the voltage level.

The surges that reach the transformers are impacted by the low-pass filtering effect due to the transformer bushings. This can “slow down” the risetime of the fast transient. Furthermore, the risk of damages from any transient that reaches the transformer winding can be effectively mitigated by transformer designs with “shield” windings (Section 2.2.4).

Results – E2. For the E2 EMP component, the main qualitative conclusion is that damages can be avoided or limited by the conventional lightning protection designs, with the caveat that no significant damage has occurred due to the impact of E1 (that always occurs immediately before E2).

Results – E3/GMD. In relation to the E3/GMD threat assessment, the main GIC indirect effect could be a system-wide impact of anomalous harmonics level. This is considered as a reduced risk event because:

i) the increasingly robust protection of reactive compensation units against harmonics

ii) power flow analyses of large areas of Eastern Interconnect showing that voltage stability is maintained even for a very large and unrealistic level of loss of reactive compensation units.

For the E3/GMD threat mitigation, GIC-blocking devices represent the best option. Preliminary transient analysis on a small bus operating with blocking capacitors shows system stability against possible onset of electro-mechanical (Sub-Synchronous Resonant) oscillations modes, except for unrealistically small values of GIC-blocking capacitances. Similar conclusions were found also for the possibility of GIC-blocking devices impacting distance protection relays, that are shown to be still effective.

Summary of Concerns for Follow-Up Activities. The studies carried on during the project highlighted some priorities to be considered for improving grid security against EMP (both large-scale and local attacks) and GMD threats.

The determination of E1 vulnerabilities, for instance via inspection of the line terminations near critical assets, should consider:

i) maximum EMP-induced surge based on grid topology vs. line BIL

ii) delay in arrester intervention due to length of connection to transformers

iii) arrester residual voltage vs. bushing and transformer BIL

iv) substation conductor layout and its impact on EMP coupling from the low-voltage side

v) transformer winding design in terms of over-insulation and internal structure to improve a uniform distribution of transient voltages

For GMDs and E3 vulnerabilities the issues to be considered are:

vi) topology-based GIC calculation, under reasonable worst-case solar events

vii) impact of harmonics from large power transformers on reactive compensation units

viii) strategic placement of GIC-blocking devices

CONTENTS

1. GENERAL OVERVIEW

1.1 Introduction

Rationale. This research effort was focused on the analysis of the threat scenario consisting in an electromagnetic pulse (EMP) coupled to the transmission power lines that are connected to a large power transformer (LPT). The rationale for focusing on this analysis is that LPTs can be considered the most critical components of the electric transmission infrastructure, both in terms of impact on the served load and time required for replacement.

The EMP Threat. From the perspective of the EMP threat characterization, the tools and results of the analysis here presented apply to the following scenarios:

i) High-altitude EMP (HEMP) generated by a nuclear explosion in the upper layers of the atmosphere. In this context, the specification of the HEMP waveform follows the International Electrotechnical Committee standard formulation [IEC,1996].

ii) Localized EMP directed to a nearby target (e.g. “briefcase” or other mobile EMP sources directed against a substation) [Radasky, 2014], [AFRL, 2016].

iii) Geomagnetic Induced Currents (GICs) that may occur in long transmission power lines due to Geomagnetic Disturbances (GMDs), *i.e.* the fluctuations in the Earth’s magnetosphere due to the impact of large solar eruptions [Wald, 2018].

Fast and Slow Transients. The type of vulnerabilities that are considered, and thus the specific type of analysis methods, are dictated by the actual waveform that represents the incoming EMP impacting a target. This leads to the establishment of two main threat categories:

- *EMP Fast Transients*: the early-time HEMP component, typically referred to as E1, the HEMP intermediate-time component (E2), as well as waveforms resulting from localized EMP sources.
- *EMP Slow (quasi-dc) Transients*: these are very slowly changing transients (in the order of 0.1 Hz or less) either caused by the HEMP late-time component (E3) or by GMDs, and for which the only concern is related to the generation of GICs.

Technical Approach. The project was developed by correlating theory, modeling and experimental testing, based on a quantitative definition of EMP and GMD coupling to the power lines, and that provided the basis for estimating the damage potential.

The analysis of the impact of the short-duration component of the EMP waveform (adopting the assumptions in the IEC standard [IEC, 1986]) follows the waveform pathway, as it propagates from power lines to reach potentially vulnerable locations near line terminations and in transformers. While this study refers to the “conventional” EMP waveform specified in the IEC standard, the analysis and test methodologies are completely general, and can be easily extended to a wide variety of different scenarios.

For GMD and long-duration HEMP-E3 components, this study was focused on the threat assessment and the mitigation solutions, with the goal of countering the immediate effects on large power transformers due to the large harmonic generation (that can then propagate on, and affect the nearby grid).

Large Power Transformer (LPT) Focus. This study takes full advantage of a large theory and experimental base of knowledge that has been accumulated since the 1980's concerning EMP and GMD impact on the power grid. The focus is to deepen previous analyses with specific focus on large power transformers.

Along these lines, the following key issues were identified as needed for providing a comprehensive assessment of the vulnerability of large power transformers to EMP and GMD threats:

- EMP-induced peak voltages reaching line terminations
- Arrester response to EMP transients (also accounting for arrester aging)
- Impact on transformer windings from EMP coupled on the low-voltage transformer side (typically from connecting conductors inside substations)
- Effectiveness of over-insulation in the first turns of transformer primary winding vs. EMP rise-time transients (that faster than the standard lightning waveforms that are typically considered for design purposes)
- Possible impact of harmonics caused in the transformer by E3 and GMDs (considering a large grid interconnect and loss of capacitive compensation nodes)
- Viability of system-wide installation of GIC-blocking devices

Fast-Transient LPT Vulnerability. The assessment of the vulnerability of large power transformers under steep-front, short-duration EMP event scenarios stems from the analysis of the coupling of the EMP waveform of the power lines, that is the primary source for the transients. This analysis included:

i) Calculation of both differential and common mode ("antenna mode") resulting from EMP coupling to a power line

ii) Evaluation of arrester performances

iii) Impact of the transformer bushing structure on the propagating waveshape

iv) Calculation of the distribution of transient waveform on transformer winding

Slow-Transient LPT Vulnerability. The vulnerability of large power transformers under the impact of GMD and long-duration EMP (E3) events is related to the generation of GICs causing a shift of the transformer operating point toward half-cycle saturation conditions.

The analysis was focused on the power flow simulation with an Eastern Interconnect model to identify possible voltage collapse and instability conditions. Worst-case scenarios were considered, looking at the local increase of reactive power levels (simulating saturated large transformer conditions) and loss of reactive compensation units (simulating reactive compensator protections that switch off-line due to large harmonic flows).

Additionally, a preliminary assessment of issues related to the utilization of capacitive GIC-blocking devices was performed.

1.2 New Learnings and Concerns: EMP Fast-transients

1.2.1 EMP-Induced Surges on Power Lines

Modeling Approaches. The analysis of the coupling of an E1 pulse on a power line has been performed through computer simulation. Both the classic transmission line (TL) approximation, as well as a fully electromagnetic calculation have been considered and cross-validated.

The TL model can be set to provide a conservative (e.g. worst-case scenario) estimate of the transient peak voltage near the line termination, with realistic loads. The fully EM model (while more computationally intensive) provides the ability of evaluating a wider set of power line scenarios, and of analyzing the distribution of voltage-to-ground on the line due to a common mode current resulting from the induced transient.

Vulnerability Assessment. The main conclusion from this analysis is that EMP-induced surges with peak voltages above the line Basic Insulation Level (BIL) are possible: this may represent a concern especially for the lower-end of the transmission line voltage range (e.g. in the 69 kV to 230 kV range), due to the lower BIL of insulators and termination components.

While, for smaller grid voltages, this is partially offset by the general trend that leads to a larger BIL-to-nominal-voltage ratio [e.g. IEEE Std. 1427-2006], the differences in the BIL specifications are significant enough for considering that a large segment of the transmission line infrastructure could be not sufficiently insulated against HEMP-E1 surges. In this case other considerations (such as impact of arresters, waveform filtering due to capacitance of both arresters and transformer bushing, flashovers and corona effects) need to be accounted for in order to determine the actual vulnerability of the transformers connected to transmission line terminations.

1.2.2 E2 vs. E1 Impact

E2 Transient Characterization. The impact of E2-type of fast transients can be considered similar to that of lightning strikes, and transmission power lines are typically designed and properly equipped for sustaining the impact of lightning. For this reason, in the context of the scope of this work, the analysis of the impact due to the E2 component of the HEMP waveform has been considered only from a qualitative perspective.

E2 Impact Scenario. One difference to consider, as compared to the occurrence of lightning strikes, is that a HEMP event is impacting a large area, quite larger than most weather systems causing lightning activity. Thus, the impact of E2 can be compared to the quasi-simultaneous occurrence of many lightning events on a very large area (*e.g.* a sizeable fraction of the continental U.S.). In these conditions the electric infrastructure could be under a significant larger stress than in the presence of the worst lighting storm conditions.

It is expected that many more localized failures will occur overall, albeit more likely occurring in the electrical distribution network (that is more vulnerable). However, on the large-scale, the electric infrastructure can count on regional-type of power dispatch coordination and redundancies so that the impact of failures on distant locations, even if occurring at the same time, remains essentially uncorrelated.

E2 Damaging Potential. Despite their qualitative level, these considerations may lead in first approximation to the conclusion that, overall, the electric transmission infrastructure can be regarded as capable to handle an E2-type of impact.

An important caveat is however the this is predicated on the assumption that the preceding E1 impact (there is no "E2" without "E1") has not damaged extensively the components that are set in place for protection against lighting strikes (e.g. shield wires, arresters and insulators). Should instead a significant damage occur from E1, the E2 wave will just amplify the damage of the HEMP impact.

Finally, special consideration should be given to those geographic areas where the lightning protection is significantly reduced, due to a statistically very limited occurrence of lightning events. Those regions are obviously more prone to a significant impact from an E2 waveform, as well as being also less equipped to withstand an E1 transient.

1.2.3 Transmission Line Arrester Response to EMP Transients

Knowledge To-Date. Earlier investigations on the vulnerability of the power grid to EMP-induced voltage surges [Legro, 1986] led to the general conclusion that transformers, especially those with large power/high voltage, may be well protected due to the presence of arresters.

The present study focused more in depth on this aspect, in order to identify if there are conditions where, even with the presence of the arresters, the voltage surges resulting from an EMP coupling on the power line may cause damages on the transformer.

Experimental Testing. For this purpose, a series of tests was performed with arresters from two different manufacturers that were subjected to fast-rise pulses, to simulate the conditions of an EMP surge coupled on a transmission line, and traveling all the way to the line termination. In this case the arrester response shows a peak transient (residual voltage) about 30% larger than the clamping voltage level. This residual voltage peak occurs when the surge is faster than the time required for the arrester's stack of varistors to switch to conduction mode. It was also verified that no residual voltage is present for slower pulses, such as a lighting test waveform.

Preliminary Assessment. While more extensive testing is required, this result indicates that there is a concern about the ability of arresters to fully provide effective protection against EMP-induced voltage surges. This lack of sufficiently fast response of an arrester could be also exacerbated by the arrester aging and deterioration due to a repeated exposure in the field to lighting and switching surges.

Early tests were also conducted to investigate this aspect (through arrester accelerated aging) but only preliminary results have been collected so far. A more extensive report on this particular matter will be provided in a follow-up publication.

Consideration for Present Arrester Installations. A further concern, although it would be relatively easy to correct, is related to the positioning of the arresters with respect to the transformer bushing connection: if the arrester is not connected directly to the bushing, the length of the connecting conductor, due to its inductance, will delay the arrester shunting effect on the line termination voltage. This, while may not be significant for a lightning strike-type of scenario, can be quite significant for the much faster EMP surges.

1.2.4 Transformer Bushing Impact on the Transient Waveshape

Transient Propagation Scenario. An EMP-induced fast-transient on a power line needs to propagate through the transformer bushing before reaching the winding: that can only happen if no flashover has occurred, and if the bushing dielectric strength is sufficiently high, otherwise the transient waveform will be clamped, with little further propagation.

While this scenario will have likely damaging consequences, it provides a sacrificial-type protection for the transformer (similar to that of an arrester), with the potential replacement of a bushing element being a more benign scenario than the need of replacing the entire transformer.

Waveshape Filtering. On the other hand, if the transient actually propagates without triggering discharges, the bushing structure, due to its shunt capacitance to ground as well as series inductance due to the internal conductor, provides a low-pass filtering effect that affects the transient waveshape (it should also be noted that arresters placed on the bushing connection provide an additional capacitive load, while still in the non-conducting mode).

Assessment of Bushing Filtering Impact. The capacitive effect of the bushing of a fast waveform has been analyzed both computationally and experimentally and led to the conclusion that an attenuation in the order of 20 dB, or larger, for the pulse frequency components above ~50 MHz is likely to take place.

In this way, the bushing provides an additional form of protection for the inner transformer structure, making more difficult for a very fast transient to reach the transformer winding.

These results were referred to a 170-kV bushing that was tested in the lab: for larger nominal voltages a similar behavior is also expected because the larger insulation thickness will be compensated by a longer structure, thus keeping the capacitance in the same range (while the inductance will actually be larger, that is an additional advantage).

1.2.5 Protection Effectiveness of “Shield” Transformer Windings

Winding Exposure Scenario. The possibility of a fast-rising, large-voltage surge induced on the power line reaching the transformer winding was also considered: this scenario, albeit relatively unlikely, could be the one that causes the most extensive damage, essentially leading to the need of a transformer replacement.

These conditions could result from a voltage surge that has not been properly suppressed by the surge arresters, nor affected by the propagation through bushing: for example, for large enough BIL design, this voltage surge may not be sufficient to cause a flashover, then travels through the bushing and eventually reaches the transformer winding.

Early-Time Transient Propagation. Since a very fast-rise, short-transient scenario is here considered, the entire voltage amplitude will be initially applied across the insulation of the first turns of the winding. This effect is well-known [Florkowski, 2012], and is accounted for by transformer manufacturers with a design that provides both over-insulation in the first turns and, in some cases, introducing an additional, floating conductor in between the turns of the winding.

Computational Results. The aforementioned countermeasures are designed for typical transients related to lightning strikes, not for the much faster EMP-induced surges. A computational model was then developed to provide an estimate of the effect of a shield conductor in the winding. The simulations show that, also for EMP transients, this technique is still effective in providing a reduction of the steepness of the voltage gradient in the EMP-transient phase.

For some transformer design, possible scenarios can be identified where the local winding dielectric strength could be exceeded: in any case the model that was developed can provide an engineering estimate that is valuable for risk-assessment purposes.

1.3 New Learnings and Concerns: EMP Slow Transients

1.3.1 GIC Indirect Effect: Generation of Anomalous Harmonics Level

Geomagnetic Induced Currents (GICs). An EMP slow transient is here referred to HEMP-E3 or GMD events that can generate a large-scale, slow fluctuation of the Earth's magnetic field. This, in turn, can couple with transmission lines connected on both ends to wye-configured large power transformers. In this case the EMP coupling may induce a common mode current (Geomagnetic Induced Current) on the line that recloses through the transformer neutral ground connections.

Harmonics Generation. The generation of GICs of sufficiently high intensity has the immediate consequence of shifting the transformer operating regime to reach a half-cycle saturation condition, with the consequent generation of a large harmonic component. In turn, this high harmonic level propagates in the power grid and may affect the protection systems of the reactive compensation units, possibly leading to voltage instability conditions and/or cascading failures.

Power Flow Analysis. This scenario, essentially an indirect consequence of the slow-transient EMP, was analyzed through a power flow model (using the PSS®E software tool). The model considered the entire Eastern Interconnect topology, and the impact of conditions resulting from the loss of capacitive compensation units (as they would go off-line, due to tripping of protections that respond to an anomalous harmonic level).

Simulation Results. This power flow tests have been performed for lines connected to wye-grounded transformers (or autotransformers) and with nominal voltage of 345 kV and above. The GICs were calculated based on the actual grid topology, for a given level of geomagnetic disturbance assumed constant in magnitude and direction.

The simulation results show that the grid is overall robust against this type of events. The voltage stability is maintained system-wide, except for an unrealistically large number of compensation units going off-line at the same time.

1.3.2 GIC-Blocking Devices

Anomalous Transformer Heating. Besides indirect effects due to the harmonic generation (Section 1.3.1), the impact of GIC can lead to transformer overheating, especially in those internal locations where heating does not occur during normal transformer operations (and thus no special design features for heat dissipation have been set in place), but where is however generated by anomalous magnetic flux patterns due to the saturation conditions.

Prevention of GIC Impact on Transformers. While thermal design guidelines could be devised to ensure that the transformer is able to safely sustain saturation conditions resulting from GICs, in this work the emphasis was put on the prevention of the GICs altogether, through the insertion of GIC-blocking devices on the transformer neutral. These devices provide a capacitive block for the very slow (quasi-*dc*) GIC transients, while offer no impediment to the current at the power frequency.

Issues Related to Adoption of GIC-Blocking Devices. A preliminary investigation was conducted on two issues that posed some concern in relation to a wide adoption of GIC-blocking devices: *i*) the potential onset of sub-synchronous oscillations *ii*) the impact on the functionality of distance protection relays.

It is also important to note that these concerns are confined only to the (typically quite small) fraction of time when the blocking devices are inserted, upon sensing a large enough GIC intensity. On the other hand, in normal operating conditions, the capacitive blocking is bypassed by a conventional conductor, thus leaving the grounding scheme unaltered.

Furthermore, the insertion of neutral capacitive blocking may lead to noticeable impact only during largely unbalanced conditions: this makes the concern of possible onset of unpredicted instabilities even more unlikely.

1.3.2.1 GIG-Blocking Device Potential Impact on Sub-Synchronous Resonance Oscillations

Test on IEEE Bus Model. A preliminary analysis on a small bus system was conducted to investigate the stability in conditions where an unbalanced fault occurs while GIC-blocking capacitors have been inserted. More specifically, the possibility of triggering sub-synchronous resonance (SSR) oscillations due to the insertion of a capacitor on a transformer neutral was analyzed with a transient simulation model in Simulink™. A standard IEEE test bus [IEEE, 1985] for SSR was modified by inserting a GIC blocking capacitor and setting a phase fault to trigger an unbalanced condition.

Dynamic Analysis. The simulation results show that the possibility of torque amplification up to large values, thus leading to an unstable condition, can be demonstrated only for unrealistically small values of capacitance inserted on the transformer neutral. However, for the typical capacitance values that would be used in a GIC-blocking installation (e.g. 2650 μF, that gives a 1-ohm reactance at 60 Hz), the model shows that the system is stable.

While these results could not be considered representative of all possible situations, the model that was developed provides a simple and effective tool for checking if a GIC-blocking installation could be considered problematic for a given section of the network.

1.3.2.2 GIG-Blocking Device Potential Impact on Distance-Protection Relays

The Simulation Model. The impact of GIC-blocking devices on distance protection relay operations was studied in a in RT-LAB® simulation model for different values of capacitors inserted on the transformer neutral. The model is based on a simple bus structure, for either 230 kV or 345 kV transmission lines, with the possibility of introducing a phase-to-ground fault at different line locations in order to establish unbalanced conditions.

Result Analysis. The simulation results indicate that, for typical values of capacitance considered for GIC-blocking applications, the distance protection relays should operate properly, and without modification of their settings, as compared to the case when no capacitive block is inserted.

Only with the insertion of a very small capacitance (100 times smaller than for a typical 2650 μF GIC-blocking device) a modification in the relay setting was found necessary, and yet still allowing the proper protective intervention. This test with a small capacitance served as a verification, for a worst-case, limit scenario, showing that the model can capture the proper dynamics.

2. COMPENDIUM OF LATEST ACTIVITIES AND PREVIOUS RESULTS

2.1 EMP-E1 Coupling to Power Lines

2.1.1 Theory Review of EMP Coupling to Power Lines

Review Paper in Progress. A review paper with provisional title "*Review of Methods for Modeling Electromagnetic Plane Wave Coupling to Power Lines*" is being compiled for submission as a review article to the IEEE Transactions on EMC.

Scope. This paper provides a compendium on the well-studied classic problem of the wave coupling to conductors above ground, from both a fully EM and transmission line (TL) modeling perspectives; it also provides a guidance in navigating through an extensive literature on the topic, as well as to provide easy-to-implement, validated, computational methodologies for realistic power line scenarios.

Full Range of Modeling Approaches. The review of the fully EM modeling methods discusses from both the mode expansion approach and the integral equation (Pocklington equation) theory approach. The TL model includes the derivations of the equations for a current and voltage in a generic position of the line, including the general case for the BLT [Tesche, 1997] equations with finite ground plane, and a discussion of TL extensions models for a higher frequency range.

2.1.2 EMP-E1 Coupling via Transmission Line Theory: Electromagnetic Reciprocity-Based Model

Scope. A computational tool was developed to provide a reliable estimate of the effects of the coupled pulse on realistic power line scenarios. This represents the key starting point for any further vulnerability analysis that involves loads connected at the line terminations.

Power Line Geometry. The basic geometries that have been considered for the simulation models are *i*) the isolated wire and the wire over ground (as in Fig. 2.1.2-1), for both perfect and of finite conductivity, and *ii*) infinite and finite line length with terminations. As is known (Fig. 2.1.2-3), that the isolated wire provides the worst-case scenario in terms of amplitude of the coupled pulse.
A methodology for the TL model extension to high frequencies and a modeling of the radiated contribution from the coupled EMP surge with power line structure have also been considered.

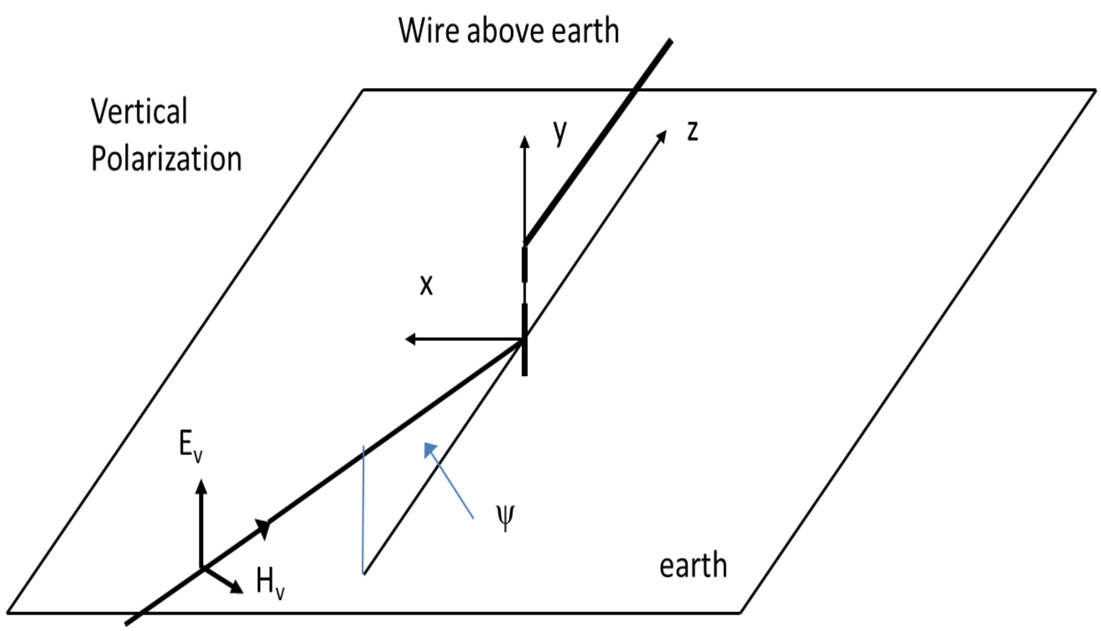


Figure 2.1.2-1. Geometry for the single conductor over ground plane considered in the TL model

Published Results. As part of this work, a formulation of the TL model based on EM reciprocity was published in [Olsen, 2018]. An example of the results in the time domain is shown in Fig. 2.2.1-2, where the voltage waveform of the line is compared for two different capacitive loads.

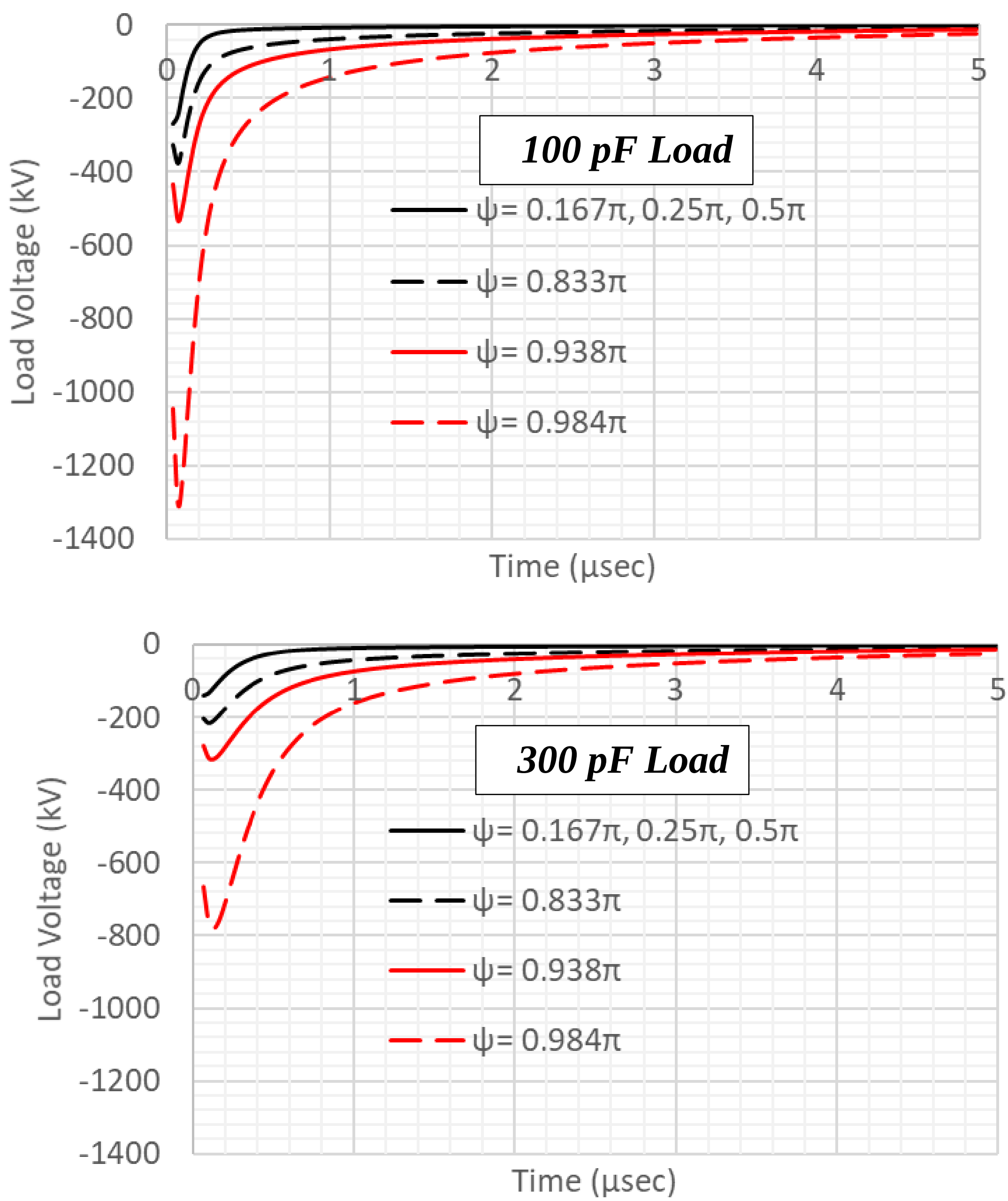


Fig. 2.2.1-2 - Voltage vs. time across a 100 pF (top) and 300 pF (bottom) capacitive load at the bottom of a vertical riser connected to a semi-infinite horizontal single conductor transmission line. A nominal incident IEC-E1 pulse is considered for a line 10 m above a ground plane with 0.01 S/m conductivity.

Single vs. Multiple Conductors. A comparison in the frequency domain between the amplitude of the peak voltage of the surge coupled to a single-conductor vs. a two-conductor transmission line is shown in Figure 2.1.2-3, for different distances between the two wires and for different angles of incidence. This test confirms the known result that a single-conductor line provides the worst-case scenario from the perspective of the line-coupled surge amplitude.

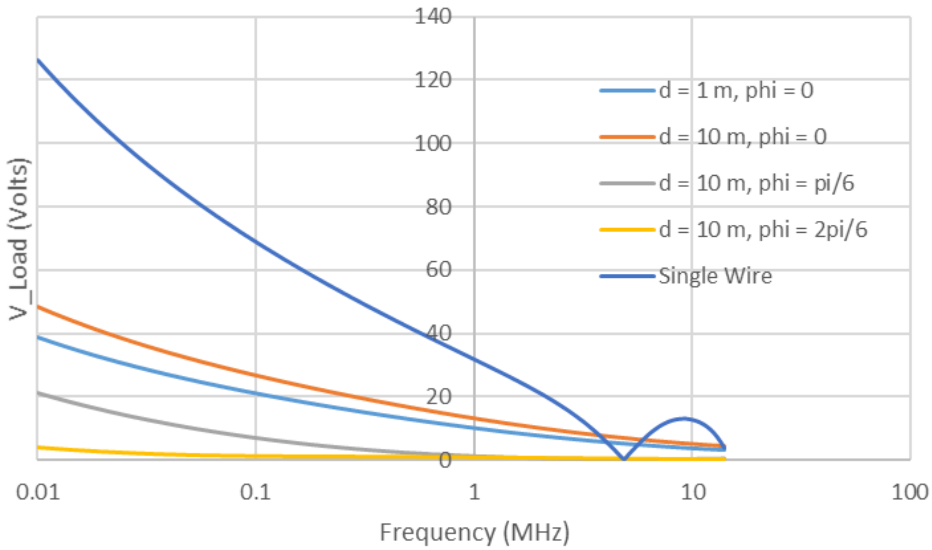


Figure 2.1.2-3. TL model test in the frequency domain: voltage amplitude on a loaded line termination resulting from EMP coupling of unit amplitude (peak E-field= 1 V/m). A single-conductor line is here compared with a two-wire line and for difference incidence angle "phi".

Ground Plane Distance Impact. Figure 2.1.2-4 shows the simulation results for the peak voltage induced on a line insulated from ground (open termination, including a small capacitance), and near a vertical riser. The voltage is plotted vs. frequency and with three different heights from ground (with lossy ground conditions). The larger vertical segment leads to a $\lambda/4$ resonant frequency. Also, as expected, the peak voltage increases with the height from ground, due to both the longer vertical segment, and the reduced balancing effect of the reflected ground wave.

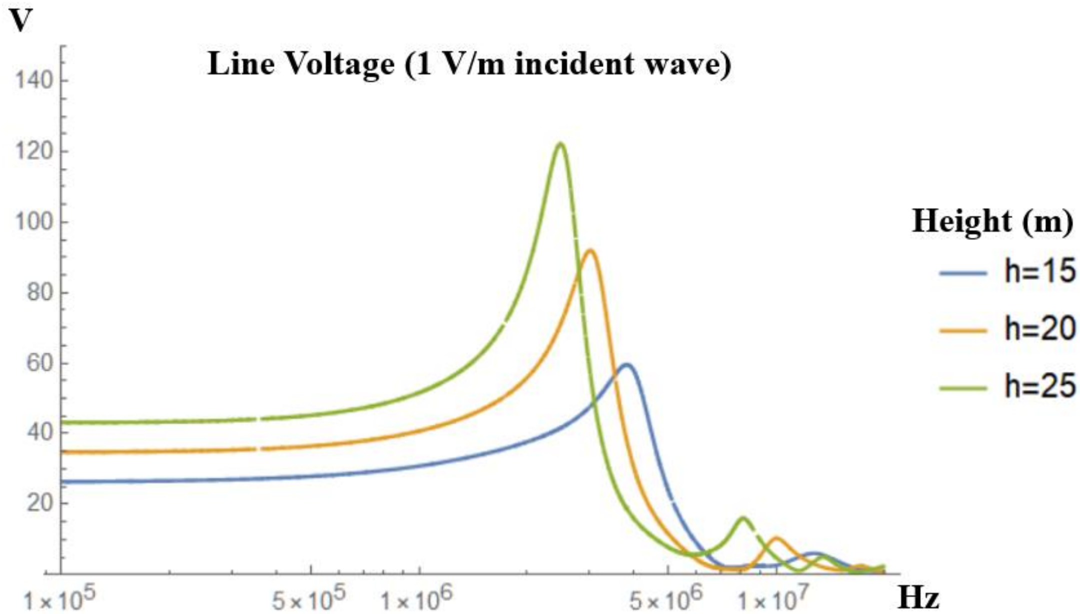


Figure 2.1.2-4. TL model test in the frequency domain for different conductor heights above ground (and same conditions as per Fig. 2.1.2-3 and 30 deg. incidence angle)

Incidence Angle Impact. In Figure 2.1.2-5 the voltage induced on the open termination of a semi-infinite horizontal line above ground is shown as a function of the incidence angle of a plane wave. The near-grazing incidence in this case is for angles approaching 180º, or π radians. The effect of the ground conductivity is also shown: when the conductivity increases the voltage peak occurs closer to180º. However, for exactly horizontal incidence, the induced voltage is zero, as expected, because there is no horizontal component of the electric field.

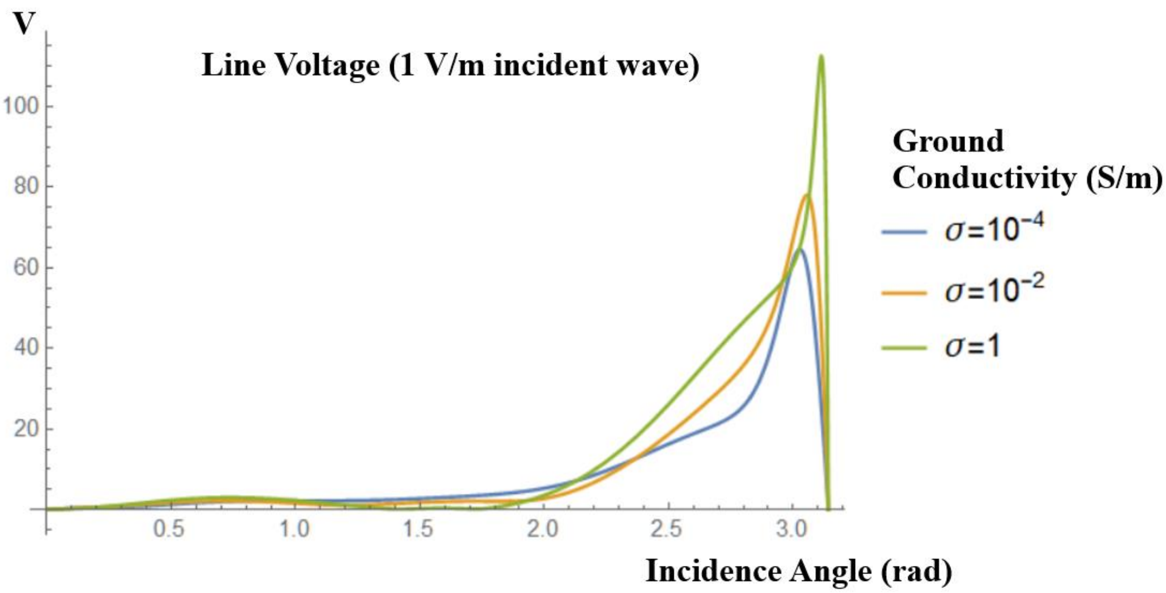


Figure 2.1.2-5. Voltage on the line vs. incidence angle and for different ground conductivities

2.1.3 EMP-E1 Coupling via Transmission Line Theory: Impact of the Wave Incidence Angle

Published Results. The analysis of the effect of incidence angle on the EMP coupling to a power line that was conducted as a part of this work was discussed in a conference paper publication [Tarditi, 2018].

Analysis of Incidence Angle Impact. The process leading to the voltage build-up for the wave impact on a line at grazing incidence angle, where a maximum is reached for a small incidence angle $\psi=\psi_{max}$ (Fig. 2.1.3-1) was analyzed in detail. This effect was well known from past literature, but the detailed physical mechanism for this effect has not been previously discussed.

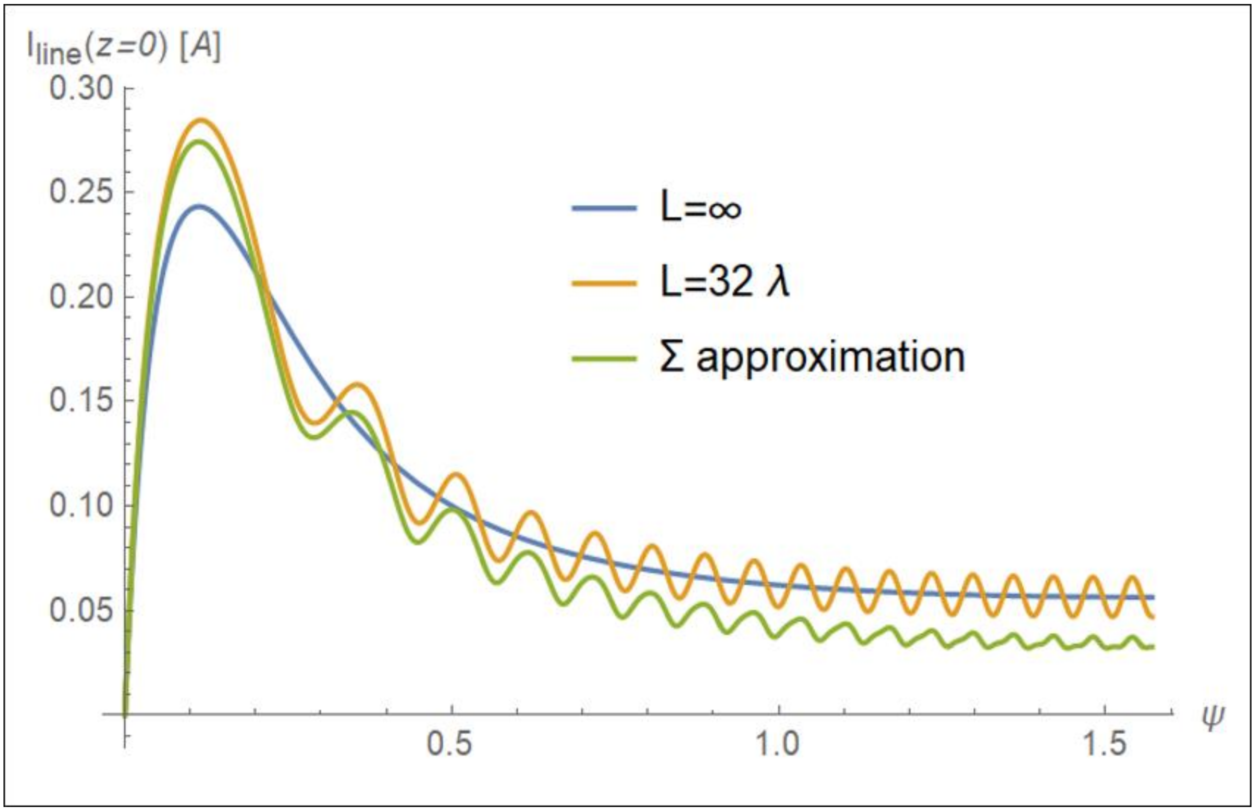


Figure 2.1.3-1. Line current amplitude vs. incidence angle ψ (with peak at ψ_{max})

The Formation of the Peak Voltage vs. Incidence Angle. This analysis shows, that due to the external incident component of the electric field, and the electric field of the travelling wave propagating on the line that is induced at each point along the line (thus, in principle, as a superposition of infinitesimal sources), can exhibit a partial in-phase superposition. This is shown in Fig. 2.1.3-2 for a set of discrete sources of electric field. This superposition is enhanced for smaller angles on incidence (with zero angle referring to grazing incidence). While the amplitude decreases with grazing incidence, this summation in phase becomes more effective, up to a certain value of the incidence angle, thus leading to the peaked profile of the induced voltage.

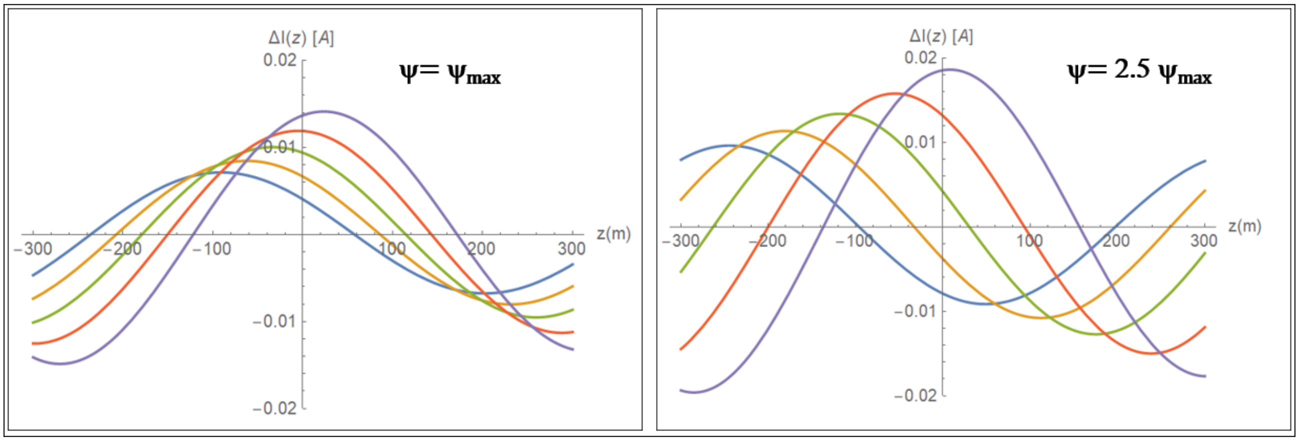


Figure 2.1.3-1. Current waveform spread at $\psi = \psi_{max}$ (left) compared to a larger ψ (right) showing that for angles closer to ψ_{max} the different current components resulting from induced sources at different positions on the line add closer in phase.

2.1.4 Fully EM Modeling for EMP-E1 Coupling to Power Lines

Research Objective. A fully EM model based on the COMSOL^{TM} software tool was developed for both verifying the TL model results as well as to characterize their limit of validity. The model computes the EMP-induced voltage between a power line termination (with arbitrary lumped-impedance load) and ground. The voltage on the line termination is computed in the frequency domain, for several frequency values. This allows to explore the differences from the TL model in the high-frequency limit.

Model Details. The basic transmission line geometry for the COMSOL model is shown in Fig. 2.1.4-1. The gap at the end of the vertical segment was included for the purpose of comparison with previous calculations with the TL model.

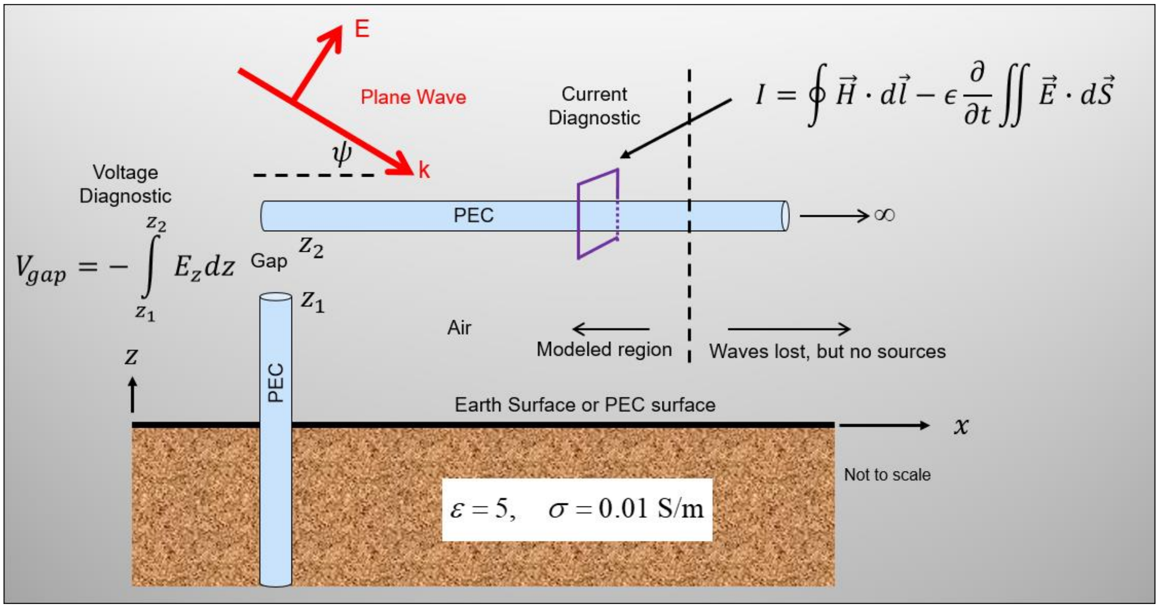


Figure 2.1.4-1. COMSOL model geometry for a transmission line over ground and a generic gap between the vertical segment and the horizontal conductor.

The Fig. 2.1.4-2 shows the actual implementation in the 3-D COMSOL computational domain.

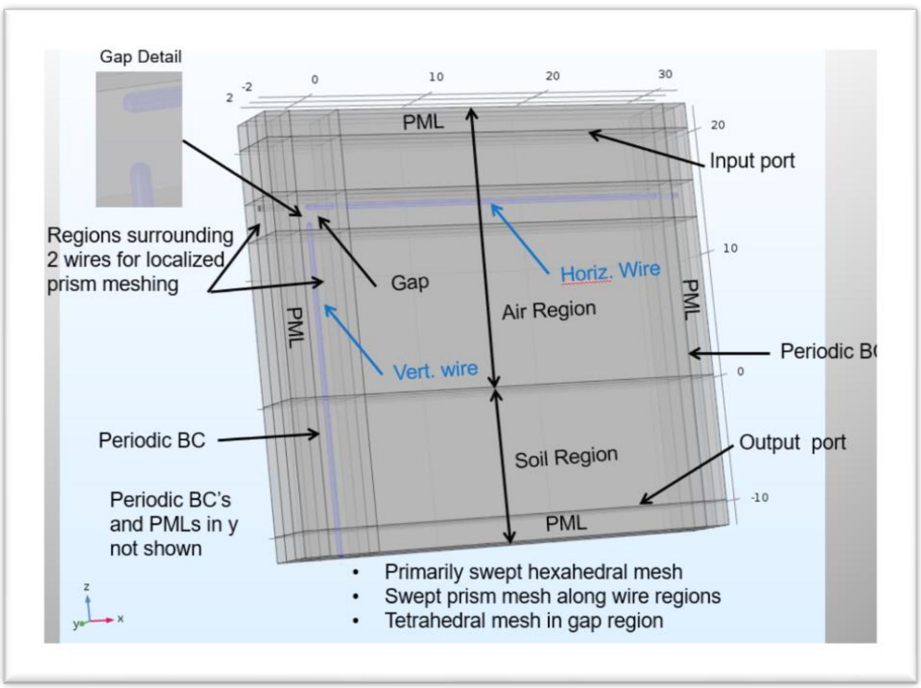


Figure 2.1.4-2. A 3-D implementation in COMSOL of the single conductor line over ground with a semi-infinite termination simulated by a perfect matching layer (PML) boundary condition.

Test Results. The COMSOL simulation model was applied to the study of the antenna mode current for a 30 m line section of a semi-infinite line model, for both perfect conducting and lossy ground plane. The current distribution over the line length for three different frequencies is shown in Fig. 2.1.4-3.

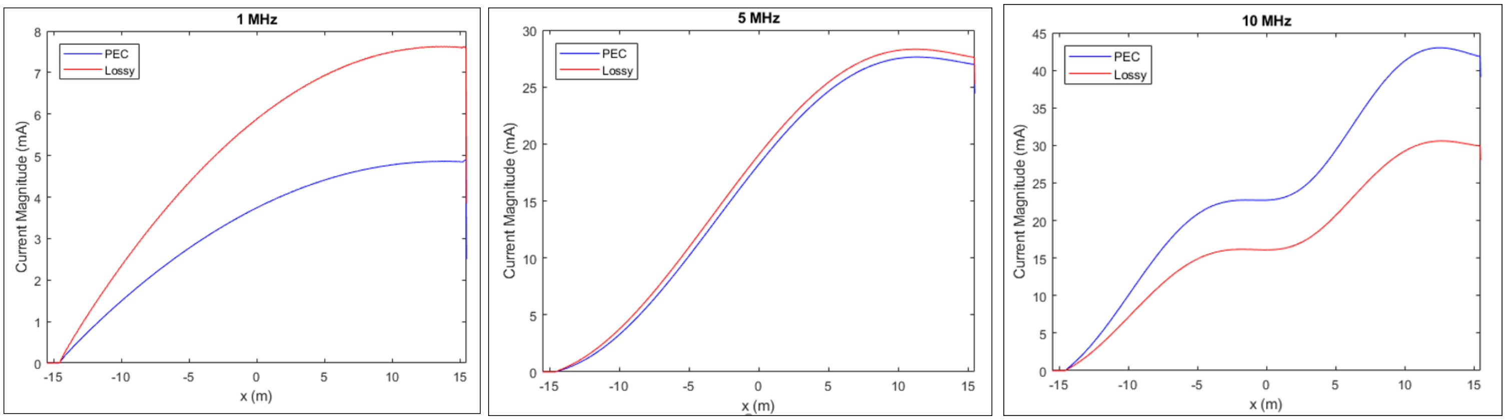


Figure 2.1.4-3. Antenna mode current distribution over a 30 m long line for three different frequencies. A PML boundary condition is imposed on the right side to mimic a semi-infinite line.

A contour a map of the y-component of the magnetic field is shown for the entire domain in Fig. 2.1.4-4, for two resonances (4.22 MHz and 14.11 MHz), and for lossy ground. The magnetic field near the conductor surface is directly proportional to the current on the line.

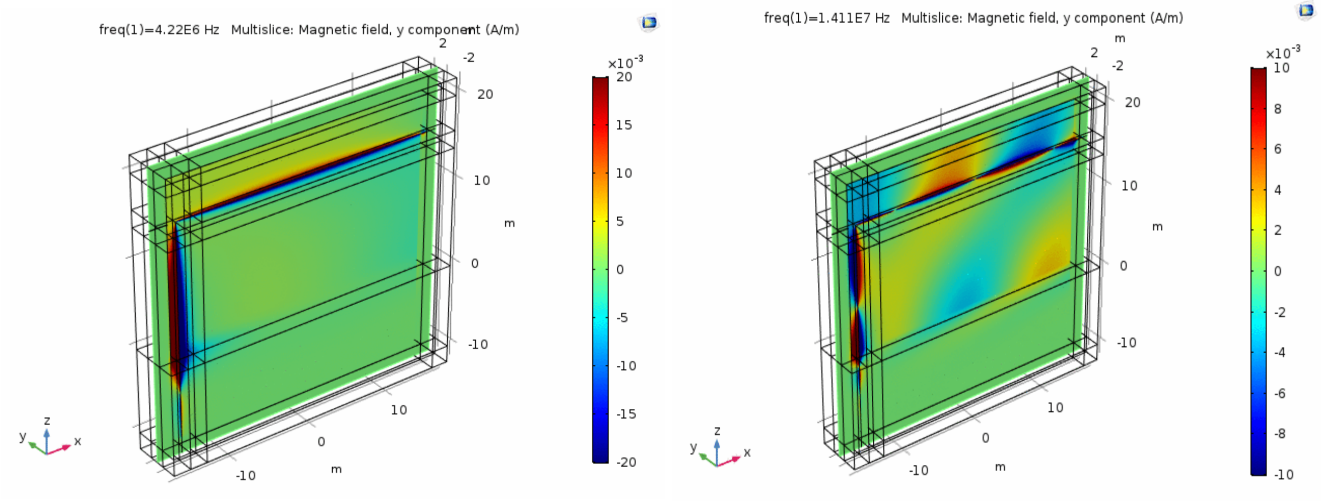


Figure 2.1.4-4. Contour map of the y-component of the magnetic field resulting from the antenna mode current distribution on a 30-m segment of a semi-infinite line model. Two different resonant frequencies are shown.

These results include the (common) antenna mode and cannot be captured in the TL model.
The simulation of a 300 m – long line, with PML b.c.'s on the right end to simulate a semi-infinite line, for a 10 MHz, 30º incident wave, is shown in Fig. 2.1.4-5.

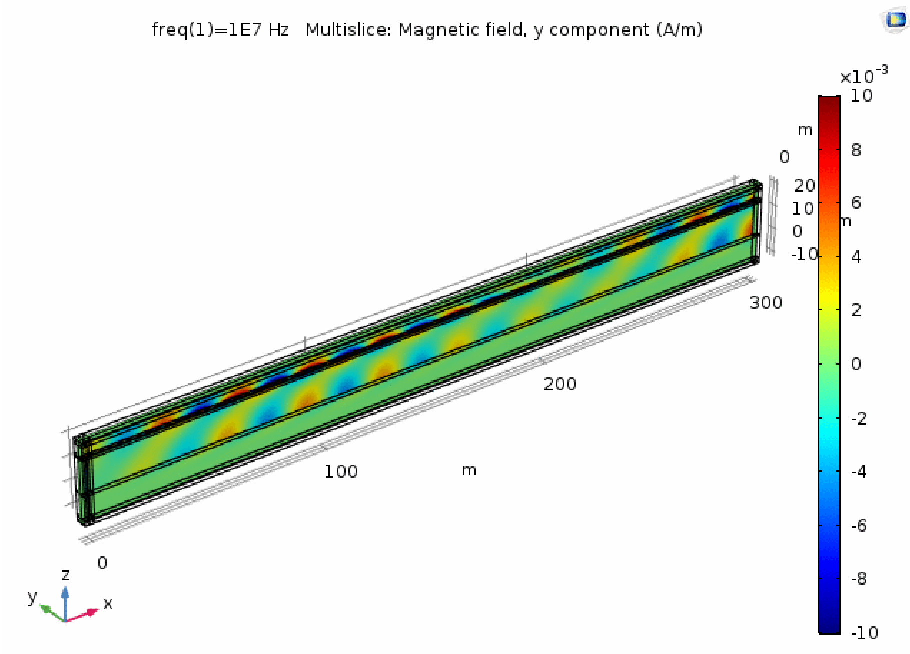


Figure 2.1.4-5. Contour map of the y-component of the magnetic field resulting from the antenna mode current distribution on a 300-m segment of a semi-infinite line model.

The data from Fig. 2.1.4-5 on the conductor are plotted in Fig. 2.1.4-6, showing a better representation of the antenna mode current pattern.

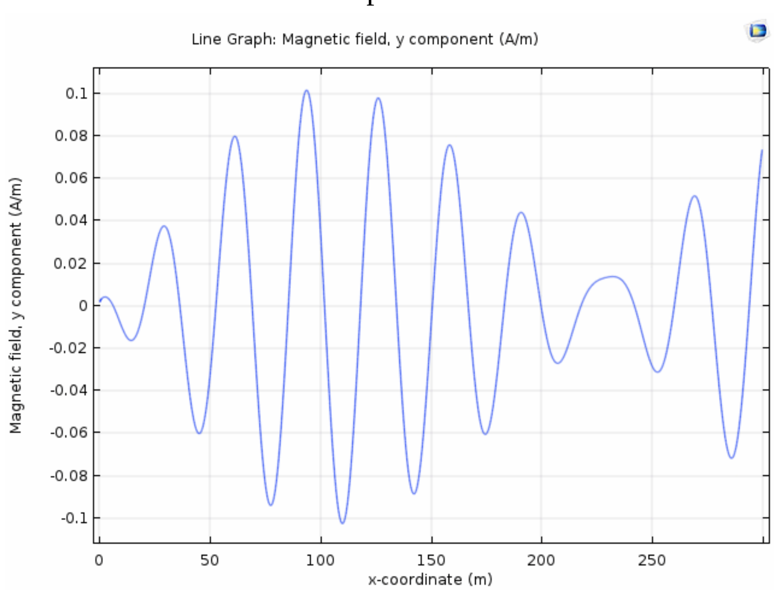


Figure 2.1.4-6. Magnetic field distribution over the line (proportional to the induced current) showing the antenna mode pattern vs. position on the line.

2.1.5 Cross-Validation

Publication in Progress. COMSOL fully EM simulations showing comparisons with the Transmission Line-based (TL) modeling, for a realistic power line geometry, are being summarized in a forthcoming paper.

Radiative Effects in the Fully EM Model. To support the COMSOL verification of the transmission line model results, the TL simulations included an additional term to account for the radiated field. This was done considering a lumped resistor to mimic the radiation resistance. This radiation resistance model is "tuned" to the resonance corresponding to the power line vertical "riser" conductor, considered as a quarter wavelength monopole (with resonance near 5 MHz, for the geometry considered).

COMSOL Validation of TL model. The TL calculation of the semi-infinite line with a vertical segment was reproduced with the COMSOL model. The TL results agree well with COMSOL at the 5 MHz resonance, but start showing inaccuracy near higher harmonics resonances (from the 3rd harmonic, near 15 MHz in this case). A detailed comparison is shown in Fig. 2.1.5-1 for ideal ground (left) and lossy ground (right). The TL model uses l/4 monopole radiation resistance, that is not accurate at the ¾ λ resonance.

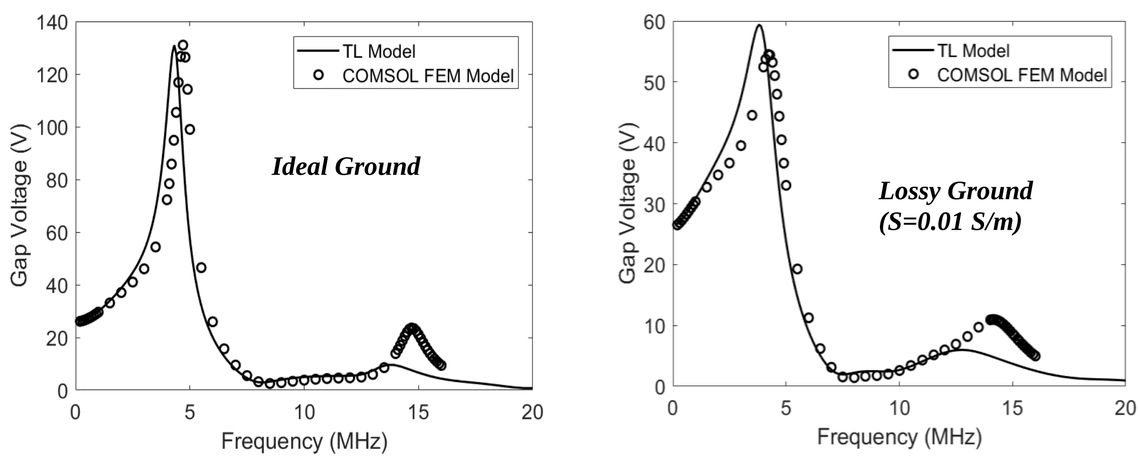


Figure 2.1.5-1. COMSOL vs. TL model comparison of induced voltage for a semi-infinite line model with vertical segment, showing the resonances on to the vertical segment.

Differences with the TL model are expected, as the TL model becomes more approximate at higher frequencies (using the distance above ground as reference wavelength).

COMSOL vs. Method of Moments Model. The purpose of the antenna mode modeling is to check the possibility of antenna mode currents leading to higher peak voltages than what is predicted by transmission line calculations. Simulations were performed with both COMSOL and the Method of Moments NEC code, for a 300 m-long, 15 m-high line over lossy ground, showing a very good agreement (Fig. 2.1.5-2).

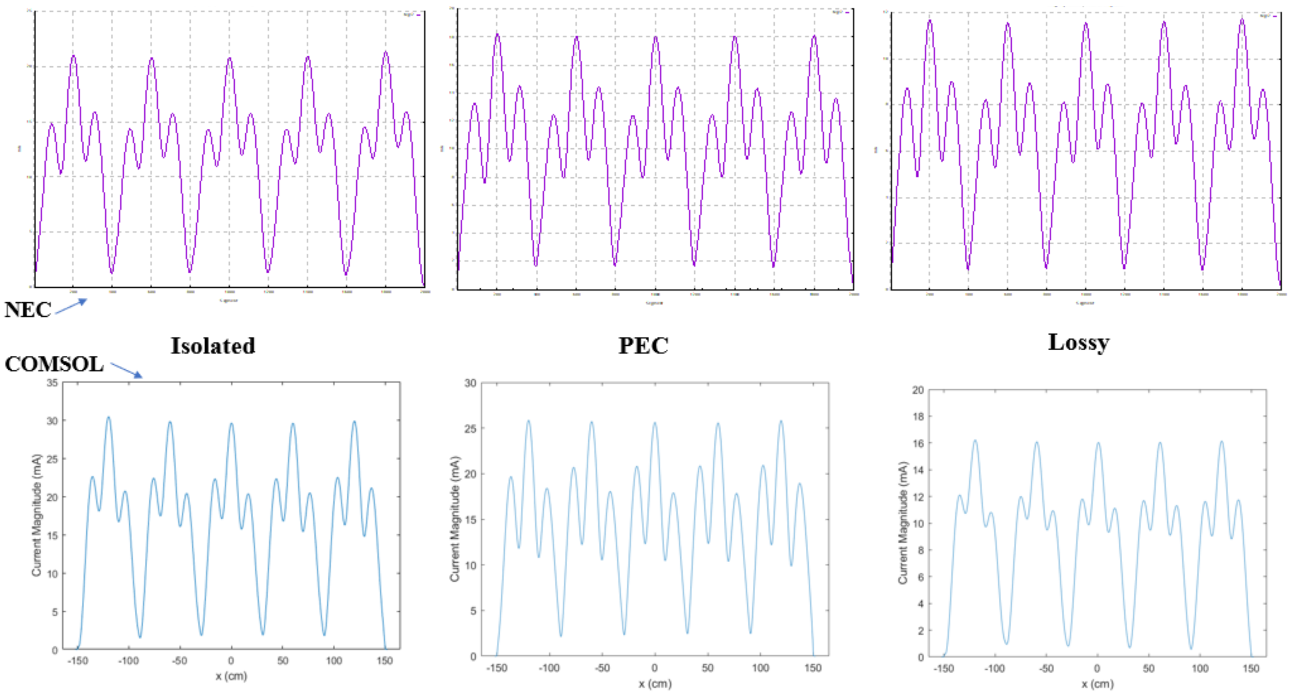


Figure 2.1.5-2. Comparison of antenna mode induced current with the Method of Moments NEC code (top) and COMSOL (bottom) models, for a semi-infinite line model with vertical segment.

A successful further validation was also performed with the EM code FEKO (with a limited resolution, trial version).

In reference to a pattern such as that of Fig. 2.1.5-2, for a sufficiently small wavelength (e.g. 20 MHz) the first peak may be sufficiently close to the vertical conductor, thus possibly creating conditions for a flashover path to ground. This case refers to the antenna mode current pattern away from the line terminations and was computed for a line configuration with vertical conductors that are grounded and isolated from the line (such power line pylons).

ANSYS Model. A preliminary verification of the EM model was also performed with ANSYS-HFSS Fig. 2.1.5-3. This result is in excellent agreement with a previously published case [Tesche, 1997].

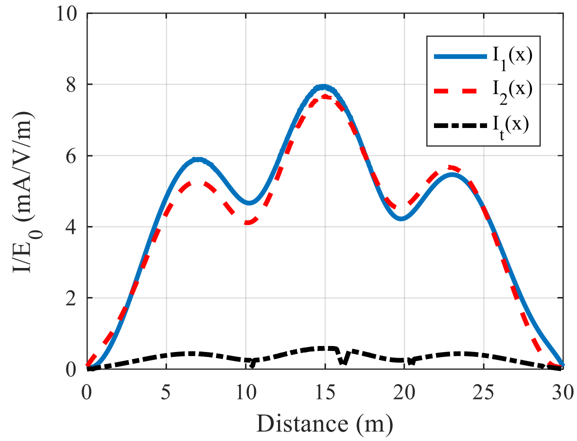


Figure 2.1.5-3. Two-conductor line (30 m long, 0.2 m separation) antenna mode calculation with ANSYS-HFSS reproduces previously published results [Tesche, 1997] obtained with the Method of Moments NEC code (in its original version). This calculation was also cross-verified with COMSOL.

2.2 EMP Waveshape Impact on Transformers

2.2.1 Transformer Bushing Simulation

Objective. A computational analysis with a fully electromagnetic model was performed to study the pulse propagation through a high voltage bushing, as utilized in large power transformer to connect the power line to the transformer winding. The purpose was to determine the peak fields inside the bushing structure, especially near the bushing connection to the transformer winding.

Methodology. Detailed simulations in COMSOL (fully electromagnetic module) with a 2D, axisymmetric geometry. Electric and magnetic field maps are computed in the time domain. The frequency-domain response up to 1.2 GHz at the bushing ports was also computed via FFT.

Simulation Results. The model provides a realistic description of the EMP-induced waveshape changes, as it is affected by the capacitive and inductive reactance distributed in the bushing structure. The waveform at the termination of the bushing provides what is required to evaluate the impact on the transformer winding.

The frequency response of an actual HV transformer bushing is shown in Figure 2.2.1-1, showing a significant attenuation above 70 MHz.

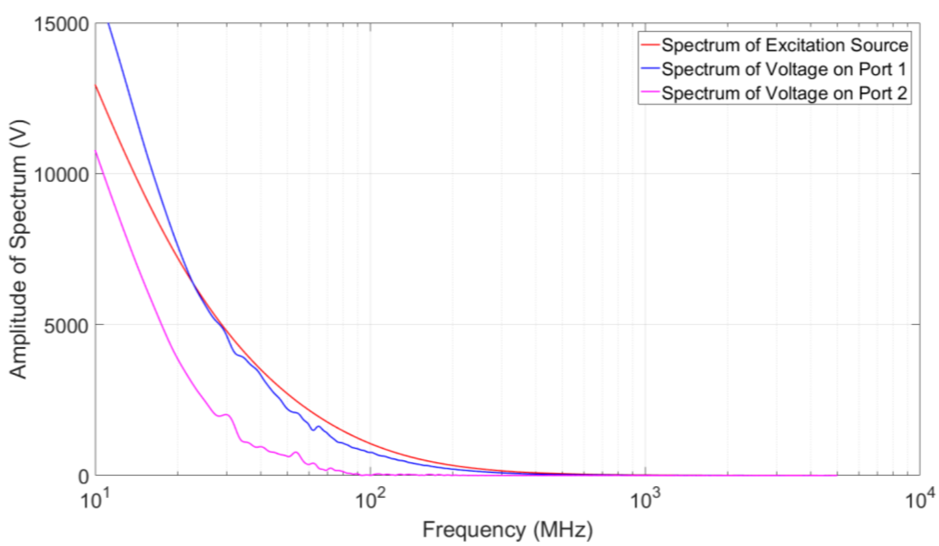


Figure 2.2.1-1. Frequency response of the bushing for a IEC-E1 waveform input source, after the injection at the top terminal (referred to as Port 1) and at the bottom terminal (Port 2).

An example of the electric field magnitude contour plots for a given time is shown in Fig. 2.2.1-2, along with to the actual design drawing of the bushing. The field that propagates past the transformer case insertion point (at about 1/3 of the height in the Figure) is what determines the potential damaging scenario near the winding.

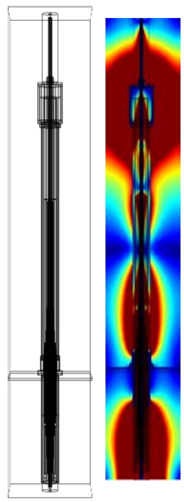


Figure 2.2.1-1. 2-D axisymmetric COMSOL model: time snapshot of the electric field transient in side the bushing, for a given waveform applied to the top terminal port.

2.2.2 Transformer Bushing Experimental Test

Test Description. A frequency response measurement of the same high-voltage bushing that modeled as described in Section 2.2.1 was performed in the frequency range applicable to the EMP threats. The test was conducted with a low-voltage frequency sweep up to 500 MHz. In Figure 2.2.2-1 the test article is shown (left) along with a data-interpolated plot of the frequency response (with and without conductive enclosure, that simulated the grounded case of the transformer).

Test Relevance. The data are collected for a low-voltage sweep and provide an accurate depiction of the filtering properties of the bushing, assuming that no arcing occurs. This allows to validate the previously shown simulation model, providing an estimate of how the waveshape from an EMP-induced surge on the line can be affected by propagation in the bushing before reaching the transformer winding.

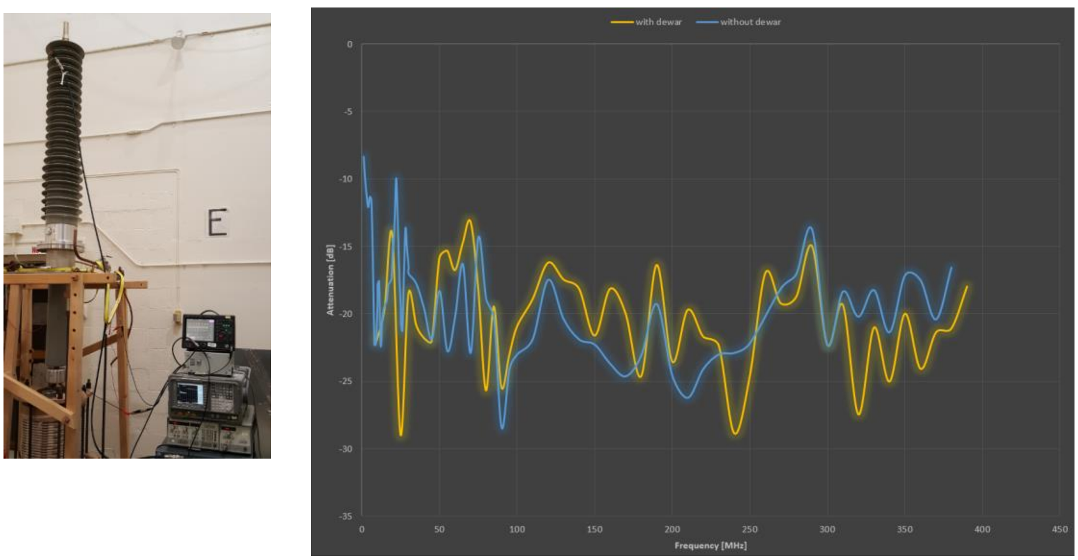


Figure 2.2.2-1. Laboratory frequency response test setup for a 170 kV bushing (left) and sweep generator response (right) showing an attenuation in the order of ~20 dB and several resonances

In Fig. 2.2.2-2, periodic moving average curves are shown for data from the same test repeated with a network analyzer and compared with the generator sweep data.

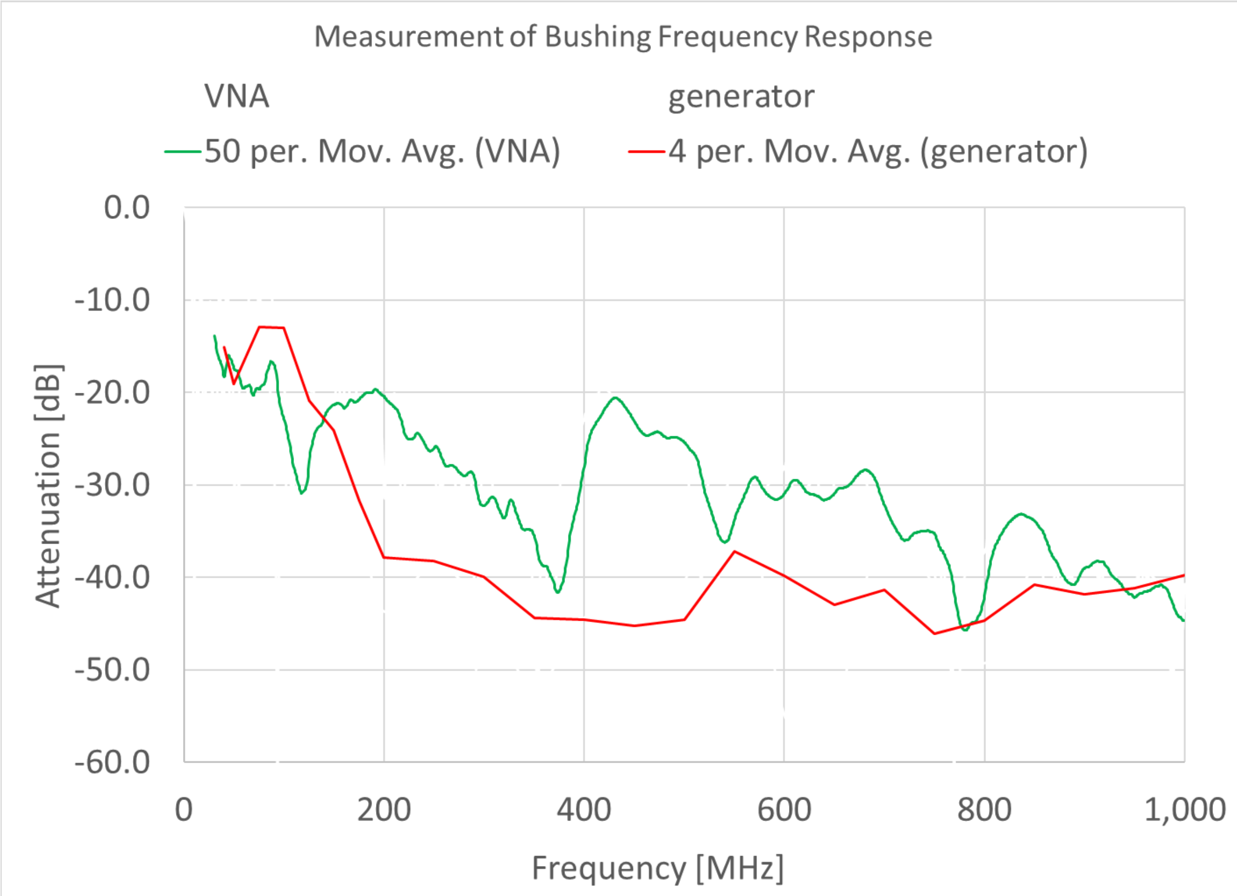


Figure 2.2.2-2. High-voltage bushing frequency response test setup shown with a smoothed moving average plots, and comparing a network analyzer test (green curve) with the data from the generator sweep test (red curve)

2.2.3 Experimental Testing on Transmission Line Arresters

Scope. High-voltage (HV) arrester testing under fast-rising pulse was performed to investigate the arrester ability to clamp very fast transients (<100 ns), *i.e.* significantly faster than the typical lighting standard waveform. Additional testing was initiated to study possible performance degradation with arrester-accelerated aging via continuous heating in furnace (requiring several weeks of heating to reach the simulated arrester end-of-life).

Test Setup. The laboratory test setup is shown in Fig. 2.2.3-1 and Fig. 2.2.3-2 illustrates an an actual test with a 500 kV Marx pulsed discharge (overexposed photograph). Two new arresters from different manufacturers, ABB and Ohio Brass (shown in the picture), with 77 kV and 115 kV Maximum Continuous Operating Voltage (MCOV), respectively, were utilized.

Figure 2.2.3-1. Laboratory setup for high-voltage pulsed testing of arresters

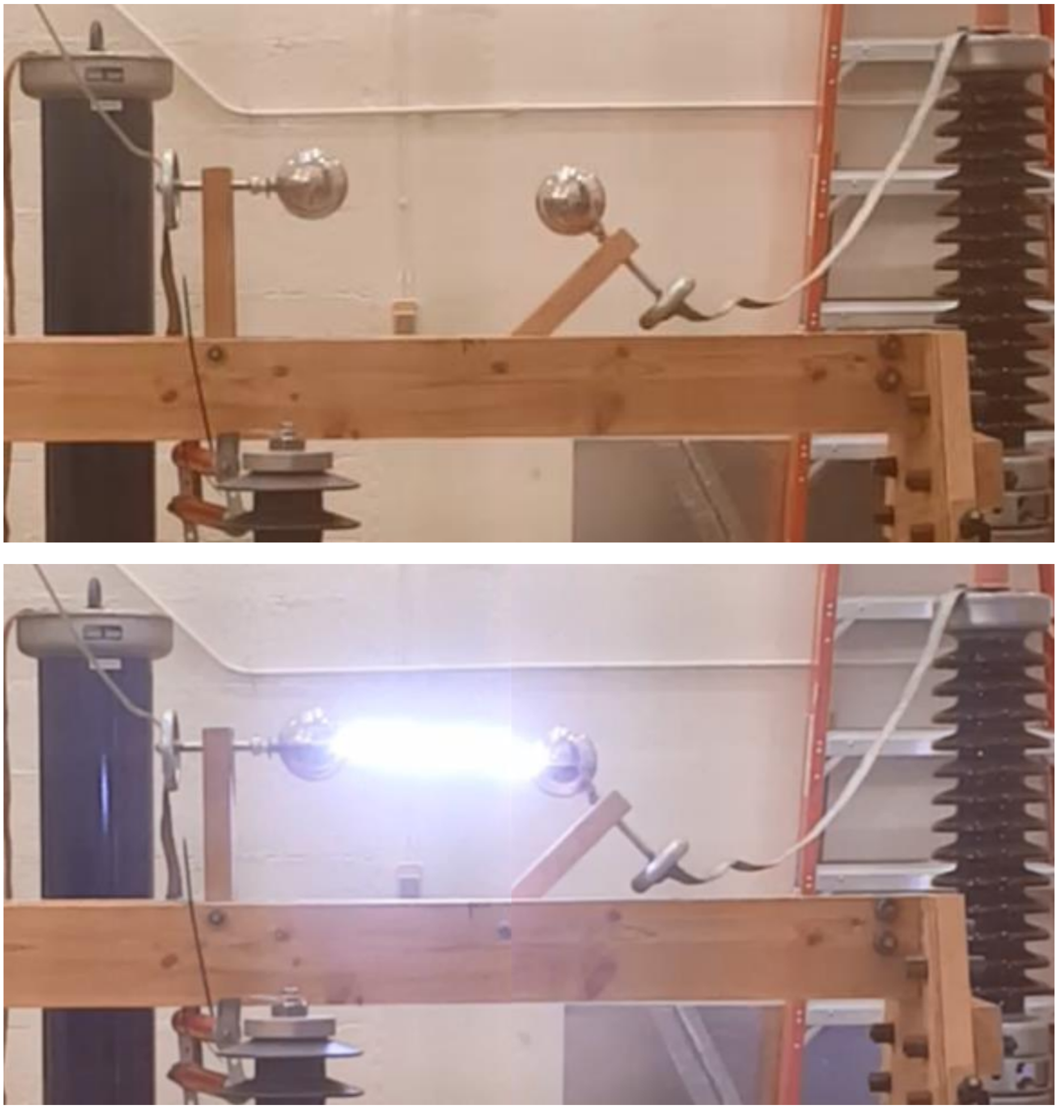


Figure 2.2.3-2. Test in progress during a 500 kV Marx generator pulsed discharge (overexposed photograph)

Pulse Response Test Results. The measurements of the HV arrester response to fast pulses indicate that a residual voltage peak occur during the early phase of the transient, reaching an amplitude up to 30% larger than the clamping voltage level that is reached after a few 100's ns. The plots in Fig. 2.2.3-3 illustrate this result for different applied voltage levels. The various curves have been shifted horizontally, along the time axis, with different offset for display purposes.

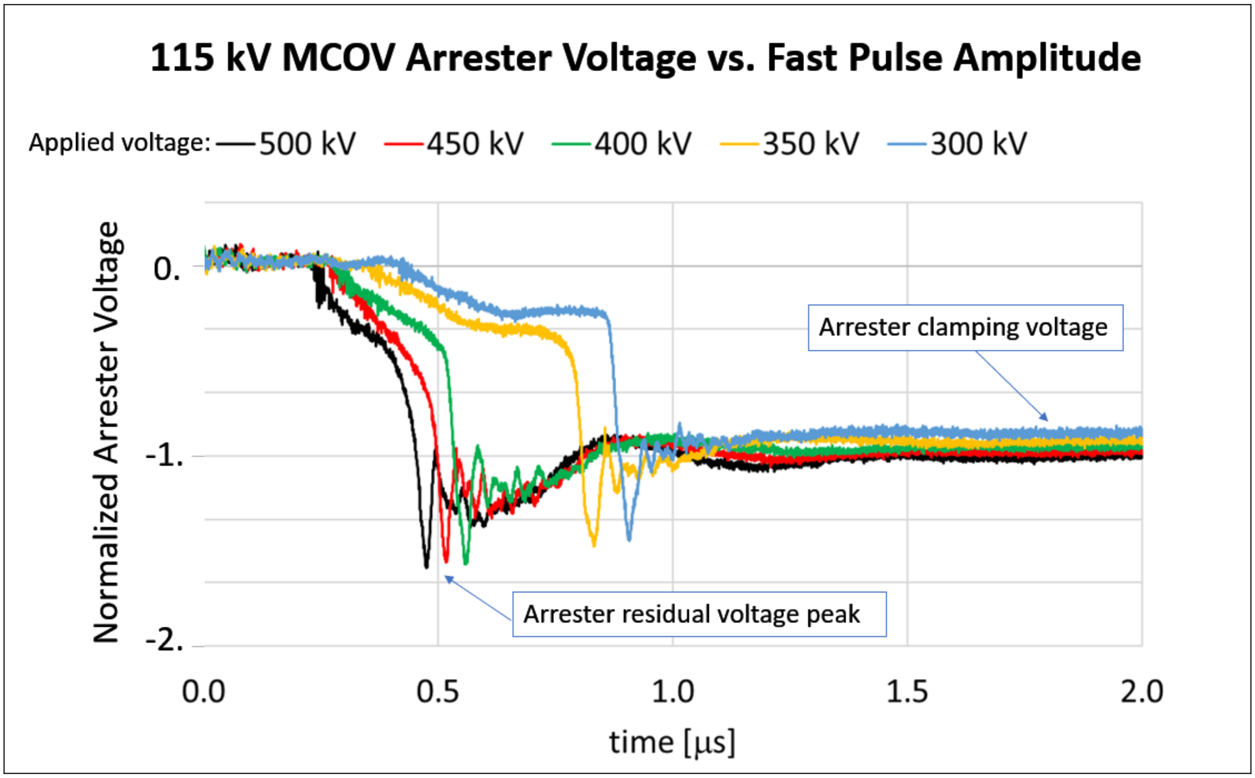


Figure 2.2.3-3. Summary of fast-rise pulse testing for 115 kV Maximum Continuous Operating Voltage (MCOV) arrester, for different level of applied peak pulse amplitude.

As the applied voltage was raised (up to 500 kV), the voltage control for triggering of the discharge was done by changing the distance of the electrode gap.

Accelerated Aging Setup. A furnace to provide a constant, temperature-controlled heating at 110 ºC was used to perform accelerated aging (based on IEEE Std C62.11-1999). Basic verifications (arrester capacitance and isolation resistance) showed integrity of the items under test after an initial phase (roughly corresponding to a half-life simulated aging of the component).

A second phase for the heating process was initiated to reach conditions equivalent to the arrester nominal end-of-life. The Fig. 2.2.3-4 illustrates both arresters placed in the furnace, with a Teflon cover sheets to improve heat uniformity.

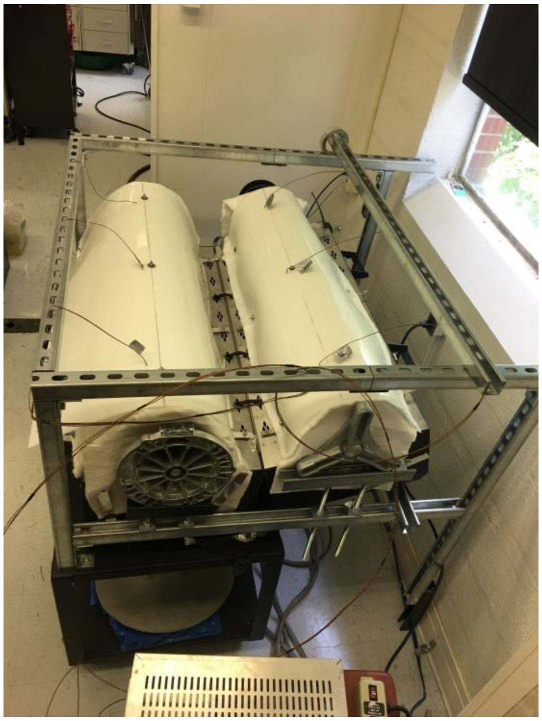


Figure 2.2.3-4. Arrester heating in the furnace with Teflon sheet covers.

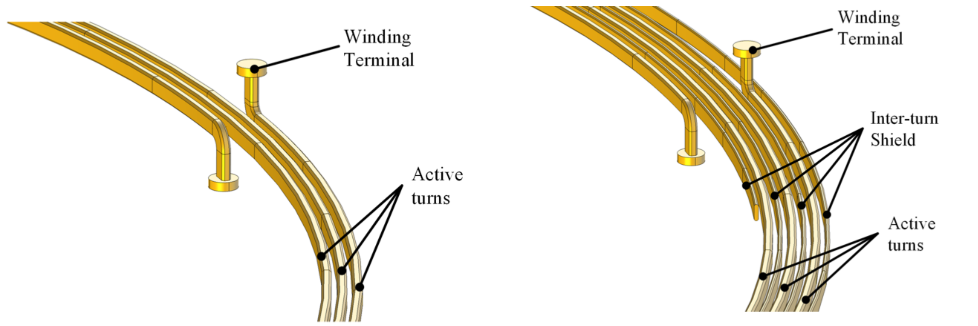
2.2.4 EMP Fast-Transient Impact on a Transformer Winding

Objective. A computational analysis with a fully electromagnetic model was performed to investigate the propagation characteristics through a large power transformer winding of fast-rise, short-duration pulse. The purpose was to establish if, in the early phase of the transient, overvoltage conditions can occur in between the first turns of the winding, especially for rise time much faster than the standard lightning reference waveform.

Test Waveshapes. A fast (EMP) or "slow" (lightning) voltage transient is injected in the transformer coil winding. A standard lightning waveform is used as a reference, and two additional waveshapes with faster rise time (an IEC-E1 radiated waveform and a variation of it that is 10 times slower) were considered.

The relevance of the fast risetime (IEC-E1) stems from EMP-to line coupling simulations that show that the voltage waveform induced on the line can change significantly, from a fast rise, essentially the same as the incident radiated pulse, to a slower response. These variations depend on the loading at the line terminations (a high impedance, or open termination will lead to a faster-rising induced pulse) and on the angle of incidence (with all other parameters being the same).

Winding Model. The first three turns of a typical design for high-power transformer winding were modeled. An additional case with a field-shaping, electrically floating, conductor inserted in between the turns (a typical design feature as well) was also considered (Fig. 2.2.4-1 and -2). This floating conductor provides a more uniform distribution of voltage across the winding, thus reducing the localized electric stress in the insulation in between the turns.



Original three-turn disc winding model without any floating shield conductor

Winding model with inter-turn floating shield conductor

Figure 2.2.4-1. COMSOL model for the injected fast-transient winding simulation: reference case and the modified case with shield.

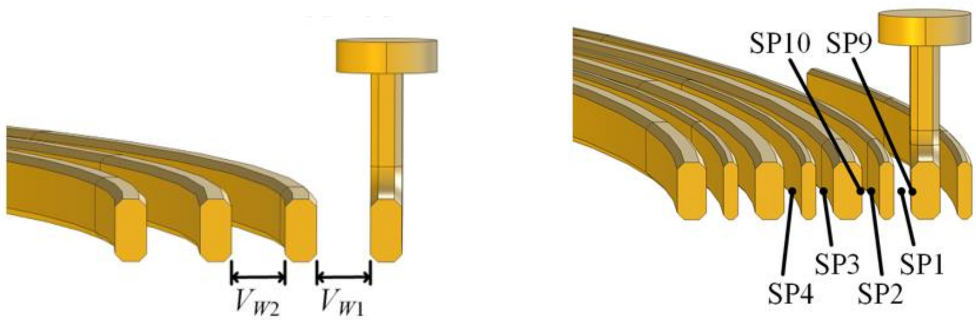


Figure 2.2.4-2. Detail of the winding geometry: reference winding (left) and case with floating conductor shield (right) with the spacing between turns kept the same as in the reference winding.

Research Impact. The voltage distribution due to the coupled EMP across the transformer winding provides essential information to establish the vulnerability threshold of an LPT design related to insulation puncture, dielectric stress, and flashovers.

The simulation provides an accurate representation of the distribution of the pulse through the transformer winding for an EMP rise time waveshape. This provides the opportunity to determine possible conditions where the standard over-insulation design in the first few turns of the winding (designed in reference to lightning pulse scenarios) may not be sufficient.

Test Results. The COMSOL time-domain simulations show the details of the pulse propagation and the non-uniform field distribution across the winding (thus potentially leading to for over-voltages). In the early times of a E1 pulse timescale (past the 5 ns peak) the field propagation is due to both the capacitive coupling and to the traveling wave along the conductor, *i.e.* the current pulse wave front. Details are shown in the Figures 2.2.4-3 and 2.2.4-4.

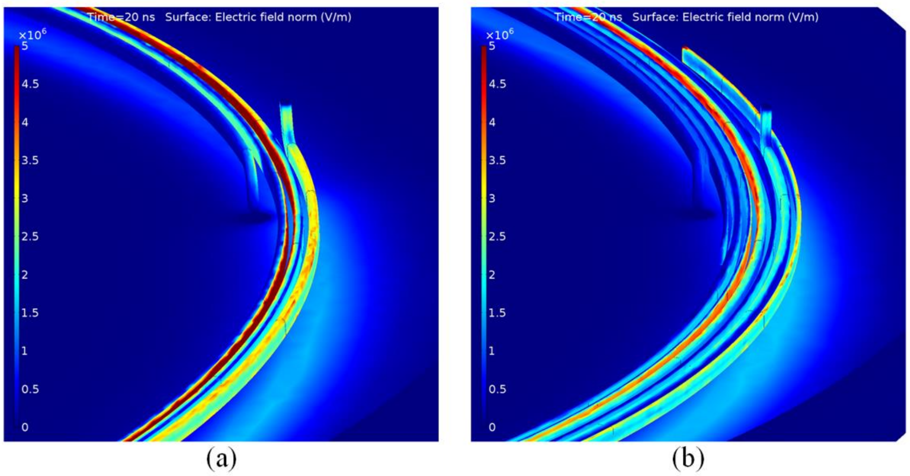


Figure 2.2.4-3. Color map of the electric field norm at a given time instant) during the propagation of a fast transient in a transformer winding: (a) original case (b) with field-shaping conductor.

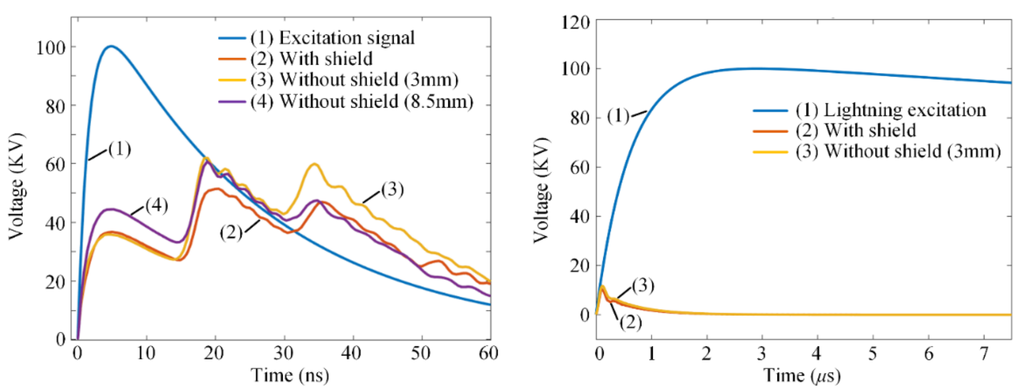


Figure 2.2.4-4. Electric field magnitude: E1-IEC (left) and lighting (right) transients in a transformer winding with different shielding arrangements.

2.3 E3-GMD

2.3.1 Power Flow Simulation for GIC Threat Assessment

Scope. Power flow simulations (with PSS/E^{TM}) have been conducted on an Eastern Interconnect model to assess the threat scenario in reference to a large-scale, potential impact of a GMD or E3 event affecting one or more large power transformers.

This analysis is focused on identifying conditions where the loss of reactive compensation units (due to protection tripping under large harmonic flows) leads to a reactive power unbalance and voltage instability.

This effort is aimed at deriving some criteria for assessing the GIC/E3 threat vulnerability of any given area, once the interconnection topology, for given reactive power compensation.

Simulation Approach. The PSS/E^{TM} simulation accounts for capacitive reactors that can be affected (and switched offline) by the harmonic flow of a transformer going into saturation: in this model, for any given large transformer, the reactive compensation capacitors that are connected to the transformer itself by a direct transmission line path are considered for removal, thus affecting the reactive power balance scenario in the PSS/E power flow calculation.

In addition to capacitors switched off line, the reactive power on the generators is increased, up to the machine design limit. In these new conditions a new critical limit for the GIC can be found.

Data from different selected areas in the Eastern interconnect have been collected to initialize the power flow simulation. Capacitive reactor compensation units that may be at risk for disconnection due to large harmonic flow have been identified based on the transmission line segments (“hops”) that connect them to transformers targeted by GICs.

Simulation Results. The table below shows two examples of these datasets, including the total reactive power levels for both generators and capacitors considered in the power flow balance simulation.

Area	Number of Transformers	Number of Generators	Generator Q (Mvar)	Capacitors 1-hop away	Capacitors Q 1-hop away (Mvar)	Capacitors 2-hops away	Capacitors Q 2-hops away (Mvar)
Area 1 (NY)	61	25	4110	3	676	6	1138
Area 2 (Chicago)	80	94	15775	4	378	45	4041

The Figure 2.3.1-1 shows the converged power balance flow for the Area 2 (as specified in the table and mapped over the related geographical area).

The value of allowed voltage magnitude increase (per unit) is shown in the color scale, with purple circles indicating locations with increase in reactive power generation, and black circles indicating locations for increased transformers reactive load.

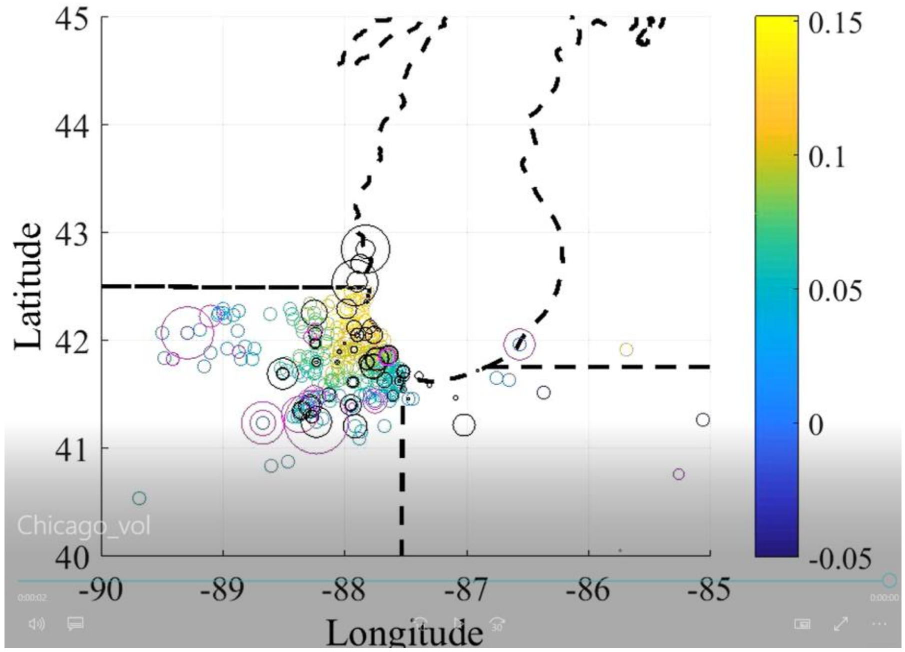


Figure 2.3.1-4. GIC simulated impact: power flow analysis for voltage fluctuations (per unit, in blue-yellow scale color) resulting from reactive power changes in transformers (black) and generators (purple).

2.3.2 GIC Blocking Impact on Distance Relay Protections

Research Objective. A hardware-in-the-loop setup testing was performed to simulate for the possible impact on distance protection relays due to GIC-blocking devices. The model provides an estimate of the effectiveness of the relay protection settings showing the transient time following a fault event before the range of relay intervention is reached.

Model Implementation. The tests were performed with the OPAL 4510 grid simulator and the RT-LAB® software. A MATLAB® SIMULINK model was devised for a three-phase transmission line. This model includes a capacitive GIC blocking devices inserted on the neutral of wye-transformer, and distance protection relays. In this study, a simulated distance protection relay system for 230 and 345 kV transmission lines (of three different lengths, 25, 50 and 100 miles) was considered with a neutral capacitor size of 2650 μF (1-ohm reactance at 60 Hz), typical for the GIC blocking applications.

The model computes the effect of the capacitive blocking device insertion on the apparent impedance of the line seen by the relays. The tests were performed for a phase-to-ground fault, for the cases of fault location at 10% or 100 % (that is right next to the GIC blocking device on the termination) of the transmission length. The analysis of impact of GIC-protection devices on "short" and "long" lines is being referred to the value of Source to line Impedance Ratio (SIR).

Fig. 2.3.2-1 shows the real-time measurements of the apparent impedance (that determines the relay operations) during the simulation of a phase-to-ground fault.

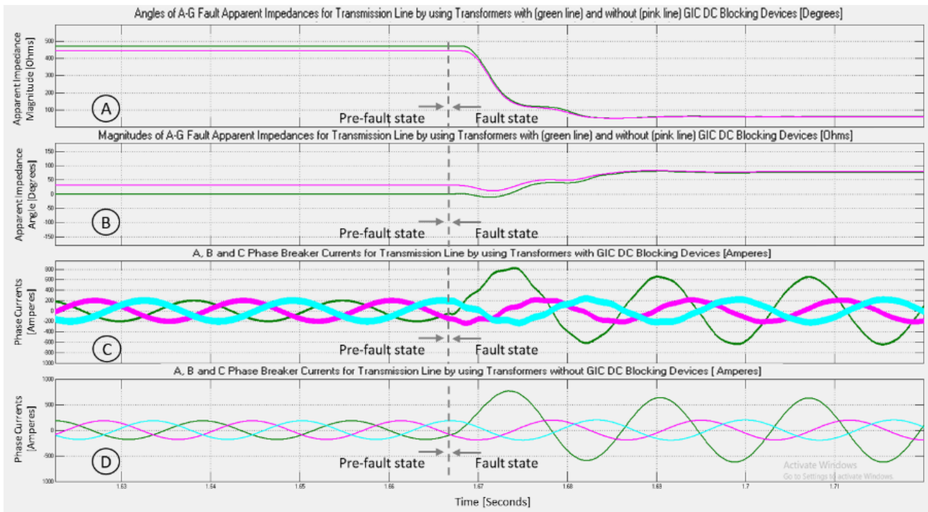


Figure 2.3.2-1. Simulation of apparent impedance variations resulting from a phase-to-ground fault in a test network with GIC-blocking devices

Simulation Results. The results show that the variation of the apparent impedance seen by the distance relay when the capacitor is inserted, for sufficiently large (and realistic) values of capacitance, is small enough (compared with the case without the capacitor) to allow for the protections to intervene without changing the relay settings.

These tests also verified that the effect of the presence of a capacitor on the neutral would require a change in the relay setting only if the capacitor is quite small, much less than what is required for an effective neutral path to ground in transient conditions. It is shown that the GIC-blocking device, for typical choices of the capacitor installed on the transformer neutral, does not require modifications in the setting of the distance protection relays, that performs as per nominal conditions.

These results have been discussed in detail in a paper that is being submitted for publication.

2.3.3 GIC-Blocking Impact on Grid Stability

Problem Definition. The research objective of this task is to investigate the time-dependent, transient stability in conditions where a line-to-ground fault occurs while a GIC-blocking device is inserted on a transformer neutral. For this case the focus was on the possible onset of sub-synchronous resonance (SSR) oscillations.

Modeling Approach. A SIMULINK transient model for a basic IEEE benchmark bus was developed and tested for the purpose of investigating if GIC-capacitive blocking devices (that principle can be either on the three phase lines, as required with autotransformers, or on the neutral) can operate without causing electromechanical oscillations (or what would be the proper parameter setup to prevent them).

IEEE Benchmark Case. The model refers to an unstable case based on the IEEE "2nd benchmark" [IEEE, 1985]) that has been developed for the analysis of sub-synchronous oscillations. This case shows a simulated instability triggered by the application of a 3-phase fault. Following this, the GIC-blocking is introduced, in this case on the neutral, and the impact on stability from the new configuration is analyzed. To determine the required unbalanced condition that can be affected by the neutral grounding path, a single-phase to ground fault was considered.

Simulation Results. Normally, a neutral-capacitor blocking device would have a bypass switch that can be closed if the current (e.g. due to faults) is larger than a given threshold, that is typically quite larger than any measured GIC. The present analysis refers to the worst-case scenario, where the capacitor is not bypassed during a fault condition.

It was found that for sufficiently large (and realistic) capacitance values the impact on the electromechanical oscillation modes is negligible. The model shows that the impact of GIC-blocking devices on the torque amplification that would trigger sub-synchronous oscillations can be contained by choosing a sufficiently large (yet very reasonable) capacitor size.

Fig. 2.3.3-1 shows the normalized torque (referred to nominal operations) vs. capacitance of the GIC-blocking device. Except for values near 50 μF (unrealistically small) any capacitor above 150 μF (still much smaller than the typical 2650 μF values considered for 1-ohm reactance at 60 Hz) shows minimal effect.

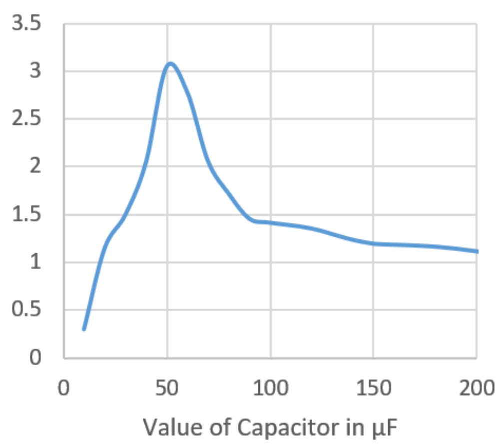


Figure 2.3.3-1. Normalized torque in the modified IEEE Benchmark SSR model vs. capacitance in the GIC-blocking device inserted on the neutral and with phase-to-ground fault conditions.

CONCLUDING REMARKS

This report discusses several technical issues related to the threats posed by the impact of EMP and GMD on high-voltage, large power transformers in the transmission grid. The analysis that was presented can facilitate the development of risk mitigation counter-measures against these threats, and provide guidance for further specialized research.

The study reflects a clear distinction, both in terms of physical effects and analysis methodologies, between the fast transients (EMP-induced voltage surges), and phenomena with slower evolution (E3-EMP and GMD) that are of concern only because the possibility of triggering GICs in long power lines.

The research results, both from computer modeling and laboratory testing, highlight the areas where further efforts will be required in order to implement in the short-term an effective preventive strategy against EMP and GMD threats.

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