Software News

While the current version of EMTP-RV is compatible with Vista (specific installation instructions can be sent on request), the soon to be released Version 2.2 is designed to take full advantage of some of Vista’s new features.

Version 2.2 is presently in beta testing mode. Meanwhile, Hydro-Québec is working on a new and significantly improved version of the plotting package, ScopeView.

The development of Version 2.3 is already in progress. Also to be released in 2008, Version 2.3 will include several improvements for handling transmission line and cable data for related models. New options will also become available for the DLL-based model developers. These options will simplify tasks and allow new services. New devices are being added for control systems and several improvements are being made for machine controls.

We have also started implementing various new scripting functions, including one which will allow drawing signals! This will significantly alleviate the task of preparing circuits from external data files or subcircuits from sophisticated masks controlling subcircuit contents and connectivity. The current approach is to use Virtual connections through visible signal names. The new approach will allow users to directly script the connecting signals in the schematic.

Many new features and models are currently being developed and shall be incorporated in future releases. We have also started compiling a new collection of examples with complete didactical information.

The Toolbox Development Group is running at full speed. The current list of members includes Electricité de France, Energias de Portugal, Entergy, NYPA and Tennessee Valley Authority. For more information, please contact Guillaume Paradis, Program Manager (guillaume.paradis@ceati.com) or Dr. Jean Mahseredjian (jeanm@polymtl.ca)

Jean Mahseredjian, creator and lead-developer of EMTP-RV
Harmonic Analysis Toolbox

The EMTP-RV development team is pleased to announce that it has received approval of the Toolbox Group to start working on a new Harmonic Analysis Toolbox based on EMTP-RV. Although it is currently feasible to build and study network models for harmonic propagation directly in EMTP-RV, the idea behind the proposed Harmonic Analysis Toolbox is to provide more models and facilities in order to simplify the tasks and increase the level of automation for the specific area of harmonic analysis application problems.

The time-domain and frequency-domain approaches of EMTP-RV provide substantial numerical advantages for evaluating multiple power quality issues within a unique software package. In addition to a new library of harmonic source models and distribution system mitigation equipments, the new toolbox will provide several powerful features, such as automatic contingency analysis and easy preparation of R-X diagrams.

Note:

The following articles have been submitted by EMTP-RV users to describe various EMTP-RV applications and uses in respective organizations. All EMTP-RV users are encouraged to contribute articles by writing to our editor, Paula Chaisson (paula.chaisson@ceati.com).

Technical Corner

AN ADVANCED INTERFACE BETWEEN THE LIOV CODE AND THE EMTP-RV

By

F. Napolitano, University of Bologna
M. Paolone, University of Bologna
A. Borghetti, University of Bologna
C.A. Nucci, University of Bologna
F. Rachidi, Swiss Federal Institute of Technology
J. Mahseredjian, École Polytechnique de Montréal

The availability of accurate models for the calculation of coupling between lightning-originated electromagnetic pulses (LEMP) and overhead power lines, such as the one proposed by Agrawal et al. [1], allows the analyses of the response of realistic lines as well as their lightning performance against indirect lightning events [2]. In this respect, the use of improved induced voltage calculation methods is also supported by IEEE Std. 1410 and Cigré-Cired WG documents [3-5].

Bearing in mind that the lightning performance of distribution networks is significantly influenced by their topology [6], a computer code for the lightning induced voltage calculation on a single multiconductor overhead line (LIOV code), based on the models described in [2], has been interfaced with some previous versions of the Electromagnetic Transients Program (EMTP-M39 and DCG EMTP96) [7, 8] in order to extend the analysis also to complex distribution systems.

It is worth mentioning that in the literature, at least three other procedures have been proposed for the evaluation of the lightning electromagnetic pulse (LEMP) response of distribution networks (Orzan et al. [9, 10], Heidalen [11-14] and Perez et al. [15] ). In the procedure proposed in [9,10], the coupling between the external incident field and the phase conductors is represented by equivalent current generators which are pre-calculated separately for each line by adopting the Agrawal et al. field-to-transmission line coupling model. The current generators are then inserted together with the usual line models to represent the LEMP-illuminated lines. Such an approach fails in taking into account non-linear local...
phenomena, such as the variation in the line-capacitance with space, necessary for instance when taking into account the corona effect [16]. Also in the procedure presented in [11-14], each illuminated line response is reproduced by means of equivalent voltage generators, the main difference being in the analytical approach adopted for the evaluation of the coupling between the external incident field and each illuminated line. The analytical approach is based on the following simplifying assumptions: i) the time behavior of the lightning current at the channel base is represented by means of a step function, ii) the time-space distribution of the return-stroke current along the channel [17,18] is represented by a transmission line (TL) model, and iii) the transient ground impedance is neglected in the coupling equations [19].

This paper presents an improvement of the method proposed in [7,8] in view of the two following main aspects: i) improved boundary condition treatment of LEMP-illuminated lines that avoids the presence of time delays and ii) integration of the LIOV code with the augmented nodal analysis technique implemented in the EMTP-RV [20-22]. The outline of this contribution is the following: we first briefly review the lightning-induced overvoltage calculation in the LIOV code, then the numerical solution of the line model boundary conditions proposed for the link with the EMTP-RV is presented. A specific section is devoted to the comparison between the results obtained with the proposed interface and experimental data obtained by means of reduced scale models [23, 24] and the triggered lightning technique [25-28]. A final section presents a discussion of the obtained results and concludes the paper.

**LIGHTNING-INDUCED OVERVOLTAGE CALCULATION IN THE LIOV CODE**

Starting from the waveform of the lightning return-stroke current at the channel base, the LIOV code implements many of the available engineering return stroke models [29] to represent the spatial-temporal distribution of the current along the channel. The LEMP is calculated by using the Master and Uman equations [30] and the Cooray–Rubinstein formula [31-33] to take into account the effect of the ground finite conductivity on the propagating field. The Agrawal et al. LEMP-to-transmission line coupling model, extended to the case of a lossy ground [2], is used to compute the coupling between LEMP and the multi-conductor overhead line, which finally allows the evaluation of the induced voltages along the line. The accuracy of the LIOV code has been verified by comparison with experimental data, both using reduced scale models [24,34,35] and full-scale setups [36].

Most studies on lightning-induced voltages on overhead power lines use a direct time domain analysis because of its straightforwardness in: i) dealing with insulation coordination problems and ii) ability to handle non-linearities that arise in presence of protective devices such as surge arresters, or corona effect.

One of the most popular approaches to solve the transmission line coupling equations in time domain is the FDTD technique (e.g. [37]). Such a technique was used indeed by Agrawal et al. in [1] when presenting their field-to-transmission line coupling equations. In [1], partial time and space derivatives were approximated using a 1st order FDTD scheme. In [38], instead, the use of a 2nd order FDTD scheme based on the Lax-Wendroff algorithm [39,40] is proposed.

**NUMERICAL SOLUTION OF THE BOUNDARY CONDITIONS OF THE ILLUMINATED LINE MODEL FOR THE LINK WITH THE EMTP-RV**

**Description of the interface**

The interface here proposed is based on the same concepts of [7, 8], namely, the distribution network is considered as consisting of a number of illuminated lines (henceforth called LIOV-lines, as their model is implemented by the LIOV-code) connected to each other through the nodal analysis equations solved by EMTP-RV. At each node we could consider the presence of components characterized by equivalent linear or non-linear shunt admittances such as: surge arresters, groundings of shielding wires, distribution transformers or other power components. The LIOV code has the task of calculating the response of the various LEMP-coupled lines connecting two nodes while the EMTP has the task of solving the line model boundary conditions through the nodal analysis equations.

For linear or non-linear line terminations, the boundary conditions of the LEMP-coupled line can be written as:

\[
\begin{align*}
\nu^v_n = & -\Gamma^v(\bar{b}_n) + \int_0^L E^v_n(0,0,t)dz \\
\nu^u_{k,\text{max}} = & \Gamma^u_{k,\text{max}}(\bar{b}_{\text{run}}) + \int_0^L E^u_{k,\text{max}}(L,0,t)dz
\end{align*}
\]

(1) \hspace{1cm} (2)

where, \(\Gamma^v, \Gamma^u, \Gamma^u_{\text{max}}\) are integral-differential operators which describe the voltage drop across the line terminals as a function of the relevant terminal currents, \(k = 0,1,2,\ldots, k_{\text{max}}\) is the spatial discretization index of the FDTD integration scheme \((k_{\text{max}}=(L/\Delta x)+1, \text{where} \ L \text{is the line length}); \) and \(n = 0,1,2,\ldots, n_{\text{max}}\) is the time discretization index of the FDTD integration scheme.

Since the numerical solution of the internal FDTD nodes \((k = 1,2,\ldots, k_{\text{max}}-1)\) provided by the LIOV code is split from the one of the boundary conditions \((k = 0, k_{\text{max}})\) given by (1) and (2) and provided by EMTP-RV, it becomes complex to explicit in a closed numerical form the boundary conditions linking the voltages and currents in correspondence of the terminal FDTD nodes, namely \(\nu^v_n|_{k=0...\text{run}}\), \(\nu^u_{k_{\text{max}}}|_{k=0...\text{run}}\). In order to overcome this difficulty, we have replaced the last spatial numerical discretization at the two line terminations \((x=0 \text{ and } x=L)\) with the numerical treatment of the travelling wave solution known as the Bergeron method or the method of characteristics [41], extended to take into account the presence of the exciting LEMP [42]. In what follows, we shall call them illuminated Bergeron Lines.

We here assume that the space and time integration steps are correlated by means of the following equation which satisfies the Courant stability condition and provides the so-called magic integration steps [42]:
\[
\frac{\Delta x}{\Delta t} = u
\]  

where \( u \) is the propagation speed of electromagnetic transients along the line (assumed to be frequency independent), \( \Delta x \) is the spatial integration step and \( \Delta t \) the time integration step of the FDTD integration scheme.

The length of the two illuminated Bergeron lines replacing the first and last spatial discretization of the LIOV line is equal to \( u \cdot \Delta t \). The Bergeron equations that describes the travelling waves in absence of external exciting LEMP, which represent the relationships between voltages and currents at the two ideal line terminations, are:

\[
v(0, t) + Z_i(0, t) = v(0, t) + Z_i(0, t) - Z_i(u \Delta t, t - \Delta t)
\]

\[
v(L, t) + Z_i(L, t) = v(L, t) + Z_i(L, t) - Z_i(L - u \Delta t, t - \Delta t)
\]

where \( v(0, t), i(0, t) \) and \( v(L, t), i(L, t) \) are the voltages and currents at the beginning and at the end of the LIOV line respectively and \( Z \) is the surge impedance of the line (assumed to be frequency independent).

In presence of an exciting LEMP field and using the Agrawal et al. coupling model, (4) and (5) read:

\[
v'(0, t) - Z_i(0, t) = v'(0, t) - Z_i(0, t) - \int_0^{u \Delta t} E_z^{s+i}(x, h, t) dx
\]

\[
v'(L, t) + Z_i(L, t) = v'(L, t) + Z_i(L, t) - \int_{L-\Delta t}^L E_z^{s+i}(x, h, t) dx
\]

By applying the FDTD method, (6) and (7) become:

\[
v_0^{n+i} - Z_i^{n+i} = v_0^n - Z_i^n - \frac{\Delta x}{2} (E_h^{n+i} + E_h^n)
\]

\[
v_0^{n+i} + Z_i^{n+i} = v_0^n + Z_i^n + \frac{\Delta x}{2} (E_h^{n+i} + E_h^{n-1})
\]

These equations provide the link between the LIOV line and EMTP-RV as illustrated by Fig. 1.

In Fig. 1 the terms \( (E_z^{n+i} \cdot h) \) are the numerical representation of \( \int_0^b E_z(0,0,t) dz \) and \( \int_0^b E_z(L,0,t) dz \) respectively, being the vertical component of the exciting electric field assumed to be constant along the \( z \) axis as generally accepted for overhead distribution lines [1].

The values of the two voltage sources \( G_0 \) and \( G_{\text{max}} \) are calculated as:

\[
G_0 = v_0^n - Z_i^n
\]

\[
G_{\text{max}} = v_{\text{max}}^n + Z_{\text{max}}^n
\]

Similar expressions define also \( G_0' \) and \( G_{\text{max}}' \) as a function of \( i_0^{n+i}, v_0^{n+i} \) and \( i_{\text{max}}^{n+i}, v_{\text{max}}^{n+i} \) respectively.

Equations (10) and (11) are calculated at each time step by means of a dynamic link library (DLL) called within the EMTP-RV simulation environment.
$G_0$ and $G_{max}$ are voltage sources added to the nodal analysis solved by the EMTP-RV. Therefore, it is necessary to define them in the solution provided by the augmented nodal analysis formulation [20-22]. In particular, each voltage source is defined by adding one row to the augmented nodal admittance matrix and, in the added row, the unknown quantity is the current of the added voltage source, while the known voltage is inserted in the known coefficients column, namely the column of the history currents sources. Together with the additional row, an auxiliary column is also added, where a coefficient equal to one is suitably inserted in order to satisfy the Kirchhoff’s laws in the loop containing the voltage source.

At the end of each time step, the currents at both line terminations, those correspond to the unknown currents of the voltage generators $G_0$ and $G_{max}$, are calculated as a solution of the EMTP-RV augmented nodal analysis. Then, (25) and (26) provide the scattered voltage values, being known the values of currents, source voltages, surge impedance and horizontal components of the exciting electric field.

Unlike the previously developed interface between LIOV and EMTP96 presented in [8], the proposed new interface does not require any time shift introduced between each illuminated LIOV-line and the boundary solution of the EMTP.

Advantages of the new interface

A comparison between the previous LIOV-EMTP96 interface and the proposed one (LIOV-EMTP-RV) is illustrated in this section. In what follows we analyze the effects related to the time-delay associated to the short Bergeron’s line external to the LIOV line used in the previous LIOV-EMTP96 interface. We make reference to the simple line configuration reported in Fig. 2 considered placed above an ideal ground and illuminated by a LEMP produced by a lightning current characterized by a 12 kA amplitude and 40 kA/µs of maximum time derivative, return stroke speed equal to $1.3 \times 10^6$ m/s and return stroke time-space distribution represented with the MTLE model. In particular, the results make reference to cases in which the line is segmented in one and five sections and with space and time integration steps equal to a) $\Delta x = 5 \text{ m}$, $\Delta t = 1.666 \times 10^{-8}$ s, b) $\Delta x = 10 \text{ m}$, $\Delta t = 3.333 \times 10^{-8}$ s, c) $\Delta x = 20 \text{ m}$, $\Delta t = 6.666 \times 10^{-8}$ s.

Fig. 2: Line geometry adopted for the comparison between previous version of the LIOV-EMTP code and proposed one

![Fig. 2: Line geometry adopted for the comparison between previous version of the LIOV-EMTP code and proposed one](image)
Fig. 3: Comparison between results provided by LIOV-EMTP and LIOV-EMTP-RV relevant to the line geometry of Fig. 2: a) line segmented in one section simulated by LIOV-EMTP96, b) line segmented in one section simulated by LIOV-EMTP-RV, c) line segmented in five sections simulated by LIOV-EMTP96, d) line segmented in five sections simulated by LIOV-EMTP-RV.

Fig. 3 shows that for the case of a line simulated by means of a single illuminated section, the two versions of the interface provide the same results irrespective the chosen space and time integration steps. On the other hand, the results relevant to the segmentation of the illuminated line in five parts results in an enhancement of the errors produced by the presence of the time-delay associated to the short Bergeron’s line external to the LIOV line used in the previous version of the interface (LIOV-EMTP96). In particular, the appropriate use of the previous version of the interface was relying on the choice of sufficiently small space and time integration steps, whilst the new version of the interface provides simulation results that are substantially independent from the width of the chosen space and time integration steps (provided they are consistent with the frequency content of the simulated transients). This last result allows the adoption of large integration steps resulting in an important decrease of computational time of particular importance when statistical studies (e.g. lightning performances of distribution networks [6]) are performed.

COMPARISON BETWEEN EXPERIMENTAL RECORDINGS AND SIMULATION RESULTS

Data provided by a reduced scale model experiment

A first experimental validation of the proposed approach is provided by the comparison between simulation results and experimental data obtained by Piantini and Janischewskyj in [23]. The measurements have been obtained in reduced scale models which were set up at the University of Sao Paulo in Brazil to experimentally evaluate the LEMP response of typical overhead distribution networks. The simulated lightning current is characterized by a nearly trapezoidal waveshape with amplitude equal to 27.5 kA, time to peak of 3.5 µs and a large time to half value (it is therefore assumed the lightning current as characterized by a trapezoidal waveshape).

In the real scale, the lightning return stroke speed is equal to 0.33·10⁸ m/s [23,25], the lightning channel height is 600 m and the lightning return stroke time-space distribution can be represented with the TL model [24]. The overhead line is placed above a metallic plate assumed as an ideal conductor; it is composed of a single-conductor as shown in Fig. 4 (values refer to the real scale).

Fig. 5 shows the comparison between measured and simulated overvoltages. As it can be seen, a good agreement is found between measured and calculated induced voltages. As already discussed in [24], possible reasons for the small discrepancies between measurements and simulations can be due to a) measuring errors being the overall uncertainty of the measuring system used in the tests lower than 5%; b) slight deviations of the stroke current from the waveform considered in the calculations; c) high-frequency oscillations associated with noise or switching of the current generation system (both of random nature); e) variation of the current propagation speed, its distortion and attenuation as it progresses upwards along the simulated “stroke” channel.

Fig. 4: Geometry of the experimental setup illustrated in [23] for the measurement of lightning-induced overvoltages in overhead distribution lines.
Data provided using a full scale model illuminated by LEMP produced by triggered lightning

A further validation of the proposed approach has been made using experimental results reported in [28] which refer to an experimental campaign carried out during 1993 at the ICLRT (International Center for Lightning Research and Testing) of the University of Florida on a real experimental overhead distribution line illuminated by an artificially triggered lightning using the rocket-and-wire technique [25-27].

The configuration of the experimental set up is reported in Fig. 6. As it can be seen, the line is composed of a phase conductor plus a neutral grounded at poles 1, 9 and 15.

The implemented LIOV-EMTP-RV model represents the LEMP-response of two illuminated lines: the first one is placed between poles 1 and 9 and the second one between poles 9 and 15. The line conductors are located at 7.5 m and 5.68 m above the ground and their diameters are assumed equal to 2.327 cm and 1.178 cm respectively, as indicated in [43].

The grounding has been modeled adopting a lumped-parameter approach by using the representation shown in Fig. 6 [44] and by segmenting the RLC network into 50 segments. The adopted grounding electrode parameters are the following: electrode length \( l = 24 \text{ m} \), \( \varepsilon = 10 \), \( R_{dcP1} = 56 \Omega \), \( R_{dcP9} = 26 \Omega \), \( R_{dcP15} = 41 \Omega \), as indicated in [43], and \( a = 2 \text{ cm} \).

For the comparison between measurement and simulations, we make reference to the lightning-induced voltages generated by the recorded stroke numbered 93-05. The stroke position for this event was the ground launcher shown in Fig. 7 and the corresponding lightning return-stroke current measured at the channel base is presented in Fig. 8. In the same figure, we have also represented an analytical representation of the measured waveform using the sum of two Heidler functions [45].
In order to estimate the influence of the return stroke speed on the incident electric field calculation, Fig. 9 shows the comparison between measurement and simulation results for the vertical component of the electric field ($E_z$) measured at ground level and at 110 m distance from the stroke location. The simulation results of Fig. 9 have been obtained adopting three values of the return stroke speed, namely $10^8$, $1.3 \times 10^8$ and $1.8 \times 10^8$ m/s adopting the Transmission Line (TL) return-stroke model. As it can be seen, the value of $1.3 \times 10^8$ m/s is the one that provides the best match with the measured incident field.
Figs. 10-12 show the comparison between measured and simulated lightning-induced voltages at pole 9 of Fig. 6. In particular, Fig. 10 show the influence of the ground conductivity on the lightning-induced voltages, whilst Fig. 11 and 12 show the influence of the returns stroke speed and grounding DC resistance, respectively.

**Fig. 10:** Comparison between measurements (pole 9 of Fig. 7) and simulations for three different values of ground conductivity ($10^{-3}$, $5 \cdot 10^{-3}$ and $10^{-2}$ S/m) relevant to the induced voltages by stroke 93-05 assuming the return stroke speed equal to $1.3 \cdot 10^8$ m/s and $R_{dcP1}=56 \ \Omega$, $R_{dcP9}=26 \ \Omega$, $R_{dcP15}=41 \ \Omega$.

**Fig. 11:** Comparison between measurements (pole 9 of Fig. 6) and simulations for three different values of return stroke speed ($10^8$, $1.3 \cdot 10^8$ and $1.8 \cdot 10^8$ m/s) relevant to the induced voltages by stroke 93-05 assuming the ground conductivity equal to $5 \cdot 10^{-3}$ S/m and $R_{dcP1}=56 \ \Omega$, $R_{dcP9}=26 \ \Omega$, $R_{dcP15}=41 \ \Omega$.

**Fig. 12:** Comparison between measurements (pole 9 of Fig. 6) and simulations for three different values of DC grounding resistances (values reported in [43], 100 $\Omega$ and 200 $\Omega$) relevant to the induced voltages by stroke 93-05 assuming the ground conductivity equal to $5 \cdot 10^{-3}$ S/m and return stroke speed equal to $1.3 \cdot 10^8$ m/s.
The overall agreement between simulations and measurements can be judged as satisfactory, especially considering the several uncertainties relevant to: i) the knowledge of the ground conductivity and its homogeneity in the surrounding of the stroke location and along the overhead line, ii) geometry of the grounding electrodes together with their parameters such as $R_e$ resistances, and iii) the geometry of the line conductors (e.g. conductors diameters which have been inferred from [43]). Additional tests are being carried out on networks with more complex topology, aimed at further showing the benefits brought by the newly realized interface.

CONCLUSIONS

This paper has proposed a new interface between the LIOV code and EMTP-RV in order to properly simulate the response of distribution networks against external electromagnetic fields produced by nearby lightning. The adopted numerical integration scheme, based on the use of the 2nd order FDTD technique, has been described together with the numerical treatment of the boundary conditions on which the proposed interface is based. Compared to the previously developed interface between the LIOV code and the EMTP96, the proposed interface does not require any time shift introduced between each illuminated LIOV-line and the boundary solution provided by the EMTP-RV. The proposed interface has been tested versus experimental data sets obtained by means of reduced scale models and triggered lightning and, as expected, good agreement has been obtained.

REFERENCES


EMTP-RV and harmonic analysis - case study - modeling a linear accelerator's harmonic impact on a sub-transmission and six distribution systems

James B. Rossman, P.E.
Senior Manager of Power Quality
Tennessee Valley Authority

Abstract

TVA PQ staff helped a distributor of TVA power evaluate options to serve a linear accelerator load at a new industrial site. Before all simulations and recommendations on service arrangements were complete, the system model had grown to include 44 distribution capacitor banks at six substations, 13 non-linear load models representing area industrial plants, and 27 combinations of series and parallel impedances representing customer loads. These multiple modeling simulations evaluated all foreseeable loading and capacitor combinations and reduced the risk of problems and complaints from others while successfully locating a new industry. Most of the EMTP simulations focused on harmonic modeling but transformer inrush flicker and pulsating load flicker were also studied showing the versatility of EMTP-RV.

Multiple EMTP-RV sub-circuits were developed to facilitate the simulation including \( I_{thd} \), \( V_{thd} \) recorders at each of the cap banks, 6 pulse ASD modules, and the most notable associated with the 5-MW linear accelerator. This sub-circuit allowed for 6 pulse or 12 pulse modeling and phase conduction control of the SCR systems associated with the front-end power electronics of the linear accelerator.

The main lesson learned from this study is that the harmonic problems can be minimized by locating the load within the network so that all distribution capacitors operate within their rated specifications at all times. The other lesson learned is that EMTP-RV, a time-domain solution program, works better in some applications than the traditional frequency-domain simulation programs.

Comments on Harmonic Analysis of Distribution Systems

Industrial facilities are accelerating the installation of PWM adjustable speed motor drives and other non-linear process equipment to improve efficiencies. These systems generate harmonic currents that flow in electrical systems. Distribution engineers need to understand harmonic flows in their system and identify key distribution equipment likely to be adversely impacted due to these flows throughout their system. Distribution capacitors tend to be key devices adversely impacted when excessive harmonic currents flow through them. If you are consistently replacing fuses on the same capacitor bank, than you might consider harmonic overloads as the root cause
for the fuse blowing. Another tale tell sign of harmonics is a humming noise (like bees in a bee hive) coming from capacitor banks.

Locating large (relative to the distribution substation transformation) non-linear loads provide a major challenge to the distribution engineer. As a customer adds non-linear loads it may be desirable to isolate the harmonic injecting load from neighbors by moving the point of common coupling (PCC) to a higher voltage level. While the large load is on the same system as others, the general objective is the move the harmonic currents from the distribution voltage level to the higher sub-transmission or transmission systems where ideally they won’t create issues. IEEE 519, Table 11.1 provides voltage distortion limits of acceptable distortion for utility busses. The distortion limits for distribution levels is 5% or Vthd and a 3% for any individual harmonic.

IEEE 519, table 10.3, provides acceptable levels of customer current injections likely to keep distribution system voltage distortion below the IEEE 519 limits. But, even if the customer injection levels stay at acceptable levels, distribution engineers must watch out for parallel and series harmonic resonances associated with distribution capacitors. Parallel resonance conditions are the most problematic since they tend to amplify currents leading to high levels of Vthd. TVA engineers have seen multiple situations where mid-sized (7 to 10MW), 12-pulse non-linear loads were fed from a dedicated distribution feeder. In each case, the distributor installed a single 1200-kvar cap bank at the customer site and unfortunately parallel resonance occurred at the 11th (or 13th) harmonic leading to high levels of voltage distortion. In several of these cases, series resonance conditions occurred at the end of another feeder causing remote capacitor bank fuses to open.

The uninitiated distribution engineer is often surprised at the level of capacitor current distortion sufficient for fuses to open. The relationship between THD and RMS current is as follows:

\[
I_{rms} = I \times \sqrt{1 + (I_{thd})^2}
\]


Capacitors are rated to operate up at 135% of rated current (IEEE STD 18). It would take approximately 90% Ithd to reach Irms levels where fuses (sized exactly at rating) start to open (assumes nominal voltage and 100% microfarad rating). At this level of distortion, the harmonics are approaching the magnitude of the fundamental. So, if harmonic levels are high enough to open capacitor fuses then this is a sign of significant harmonic resonance. Repetitive fuse openings should be viewed as a significant problem needing system evaluation to determine the root cause leading to this event.

If harmonic voltage distortion is a concern (or capacitor fuses operate routinely), then harmonic troubleshooting may be warranted. A clap-on, hand-held, harmonic amp meter and a line-insulated bucket truck (for safe measurements) are a good combination when troubleshooting distribution harmonic issues. There are also hot-stick harmonic meters that allow measurements without the use of a bucket truck. Besides capacitor Ithd, voltage THD measurements are helpful to identify the extent of the harmonic problems. All these measurements are the basis for setting up a base case of harmonic computer simulation. Computer simulations help the distribution engineer understand the system harmonic flows resulting from the customer injections, the impact of capacitors/inductances, and the success of moving these currents up to the transmission level without creating unwarranted levels of voltage distortion.

EMTP-RV and Harmonic Computer Simulations

Over the last three decades most computer harmonic simulations were modeled using frequency domain methods. Text-based, time domain, programs (like EMTP) were more time consuming and complex relative to programs specifically designed to solve harmonic flow simulations. Unfortunately, on occasion, these frequency-domain programs had limitations that led to simulation inaccuracies. For example, many use fixed current injections for nonlinear loads that
didn’t change as voltage distortion increases. Most times this doesn’t lead to problems but occasionally it can lead to significant errors.

EMTP-RV has recently been developed with the funding support of EPRI. This program is graphic, one-line component based, program and relatively easy to use (versus the previous versions of EMTP). With its time-domain approach, it is possible to evaluate multiple PQ issues with only one software package. For example, it is possible to model transformer inrush, capacitor switching disturbances, load created voltage flicker, and harmonic flow simulations with the same base model. This is especially handy when trying to evaluate potential PQ issues when locating new industries. One aspect of EMTP-RV is similar to standard frequency domain programs - the ability to perform frequency scans of the network.

EMTP-RV has several features that help to quickly build a working model. For example, sub-circuits provided with the software allow for quickly placing groups of complex circuit elements into a developing model. User friendly, Windows-based commands such as copy and paste allow for quick learning of key commands and the default library of components help the novice get a model running quickly. For those with some experience with modeling, it is possible to customize sub-circuits. For example, a combination of linear and nonlinear components allows for precise modeling of plant load. The scopes mode allows for simulation outputs such as voltage and current waveforms or more complex single phase outputs like waveform THD or RMS. There also are three phase outputs available such as real and reactive power. With all this capability it is easy to install measurement components at locations where actual measurements have been recorded. Once again, when possible, it is extremely important to generate a simulation base case that matches actual readings.

### Linear-Accelerator Case Study Simultaneous Using EMTP-RV

A distributor of TVA power wanted TVA assistance evaluating service options for a new industrial customer who plans to occasionally test 6-pulse, 5-MW, linear- accelerators targeted for military applications. Linear-accelerator use is becoming more common place and you may have experienced their impact when riding a newer type roller coaster - they get you going fast! Originally, the distributor thought that the load might be served from an existing substation dedicated to serving nearby industries. Unfortunately, our simulation results showed that levels of voltage distortion would not allow routine service from this substation. It was determined that a dedicated 46:13-kV on-site substation would be evaluated. In order to fully evaluate the harmonic flows, a complex model was generated containing 1-161-kV equivalent impedance, 1-161:46-kV transformation, 46-KV sub-transmission system, 2-161:13-kV substations (existing), 2-46:13-kV substations (existing), and 2-46:13-kV substations (new). All these systems are shown in the Attachments labeled EMTP-RV 1, 2, 3, 4, 5, 6.

The phase conduction simulation control of SCRs (see Attachment - Sub-circuit 1) was developed with the support of EPRI employee Harish Sharma. SCRs make up the front end power electronics of the linear-accelerator. The firing angle was delayed for SCR conduction to adjust the system to operate at 80% power factor (linear accelerator operational specification).

The 46-kV sub-transmission system was modeled using PI equivalent mutually-coupled components. All 13-kV distribution overhead circuits were modeled with R and L mutually-coupled components. For each feeder, all distribution feeder impedances were included up to the location of the last capacitor bank on the feeder. The model contains 44-13-kV capacitor banks ranging in size from 600-kvar to 1500-kvar (see Attachment - Sub-circuit 2 for typical 600-kvar sub-circuit).

Customer load resistance (P) and inductance (Q) equivalents provide an alternate path for harmonics to flow (instead of forcing all harmonic load currents from the load toward the source). It was determined by revenue metering data and previous plant audits, the level of nonlinear and linear load for each industrial plant. The 27 linear loads were modeled with sub-circuits with 50%
series R, L components and 50% parallel R, L components (see Attachment - Sub-circuit 4). Each sub-circuit load was adjusted to meet the real (P) and reactive (Q) linear power levels for the plant.

The 12 existing plants with nonlinear loads were each simulated with sub-circuit containing a 3-phase,13-kV:480-V step down transformer and downstream 480-V rectified load model (front end of ASD - see Attachment - Sub-circuit 5). Each sub-circuit load was adjusted to meet the real (P) and reactive (Q) nonlinear power levels for the plant.

The fall season was chosen for the worse case simulations since this represented the season with the lightest loading. The residential loads, industrial loads and capacitances were adjusted to allow substations real and reactive power levels to match actual loading from fall power billing data. There were estimated to be 32 out of a total of 44 capacitor banks in operation during the fall loading period. Besides adjusting for the worse case season, the adjustment for time of day operation of the linear-accelerator was also warranted. Fortunately the plant manager plans testing the linear-accelerator during day-shift, weekday timeframe. Modeling was fine-tuned to account for this loading during the fall simulations.

Linear-Accelerator Case Study - EMTP-RV Simulation Results

As mentioned earlier, the linear accelerator facility is located in the middle of an existing industrial park and ideally should be served by the substation that feeds other loads in this park. It was showed by modeling that the voltage distortion could be limited to IEEE 519 limits if the distributor removed most capacitor banks during testing. This required testing only during off-peak times and during weekends when other industries weren’t operating. The linear-accelerator plant manager rejected this limited testing periods so the 46-kV attachment was considered next. The interconnected to a nearby 46-kV system requires approximately a 1 mile line to be constructed.

As an extension to this study, the distributor asked TVA to evaluate the possibility of installing a second 46:13-kV transformation at the linear-accelerator site. This new substation (ES) is targeted to service three future industrial sites. Since the two new substations are located at the end of the same 46-kV tap line, the PCC for the linear-accelerator is immediately on the source side of the 46-13-kV linear-accelerator substation. The new industrial substation (ES) 13-kV bus has the highest potential for voltage distortion due to linear-accelerator operation. Limiting the capacitors on the ES substation helps keep voltage distortion under IEEE limits. The modeling shows that the limit is 1800-kvar (total). Adding more capacitors increases the series resonance effect and drives more of the nonlinear load toward the new substation and less heading through the 46-kV sub-transmission system and on to TVA’s 161-kV system. It was determined that this substation could be under-compensated with 1800-kvar of capacitors without problems.

The EMTP-RV scope outputs are accessible by the program SCOPEVIEW (provided with EMTP-RV). The Attachments labeled Results 1, 2, 3 summarize Vthd, Va-n waveform and la waveform for the linear-accelerator dedicated bus. Note that the simulations last 120-ms and the linear-accelerator start operating at 60-ms. The scope outputs should be viewed during steady-state harmonic performance. For example, 40 to 60 ms is steady-state with no linear-accelerator operation and 100 to120-ms is steady-state during linear-accelerator operation.

The Attachment labeled Results 4 shows the Vthd at all major busses in the simulation with the ES (new 46-13-kV industrial substation) and LA substation approaching 4.5% Vthd during the LA testing. Note that the other nonlinear loads create harmonic current flows resulting in base level Vthd levels up to 2.2%. The Attachment labeled Results 5 shows the Ithd at all major busses in the simulation.

The harmonic flows due to nonlinear loads tend to show up in capacitor banks throughout the network. In particular, capacitors tend to form parallel and series resonant conditions that attract harmonic currents. Therefore, by studying the simulation outputs of Ithd flowing through each
capacitor bank and the Vthd at each capacitor location, resonant problem locations can easily be
identified. The Attachment labeled Results 6 shows the Ithd for each capacitor location and it
shows no capacitor bank current exceeding 35% Ithd. At this Ithd level, the capacitor currents
should all be well below the 135% current limit for capacitors. The Attachment labeled Results 7
shows the Vthd at each capacitor location. No capacitor bank locations show Vthd levels above
4.7%. The key point to consider is that Vthd at capacitor locations tend to be higher than at the
substation bus. If you can reduce the Vthd at capacitor bank locations to levels below 5%, than
the substation level will also remain below 5%.

Summary

Industries are adding nonlinear load systems as they modernize their facilities. These nonlinear
loads inject harmonics into distribution systems. Distribution engineers need to be aware of
harmonics when industrial plants expand or when locating new industries. As part of the
evaluation, harmonic simulations may we warranted. EMTP-RV is a useful tool to evaluate
harmonic and other PQ issues. A large multi-distribution system simulation example was
shown using EMTP-RV as the evaluation tool. This case study shows that complex systems can
be quickly constructed using sub-circuits and other handy features of EMTP-RV. The linear-
accelerator EMTP-RV case study shows that capacitors tend to be the key when evaluating many
harmonic flow studies. Capacitors tend to tune systems toward parallel and series resonances.
One way to insure that system problems are identified is to study the Vthd at capacitor bank
locations and the Ithd of the currents flowing through the capacitors. This is a quick way to
identify resonance issues. Finally, if the voltage distortion and current distortion associated with
the capacitor banks is minimized, then system busses will also see harmonic issues minimized.
EMTP-RV 4
Node S Page (4) - 46-kV: 13-kV Substation Serving Only Residential Load
EMTP-RV 5
Node N Page (5) - 46-kV: 13-kV Substation Serving Only Residential Load

Node N

DY 2

46/13.2

P_N

scope

Q_N

scope

p13

THD_N

THD_Calc

V THD N

V N

scope

p(t)

V_N

scope

+1|1E15|0

-1|1E15|0

PQ Load2
3.45MW
1.4MVAR

PQ Load8
3.45MW
1.4MVAR

PQ Load7
3.45MW
1.4MVAR

N_C214A
Cap_1200_THD

N_C214B
Cap_1200_THD

N_C214C
Cap_600_THD

N_C224A
Cap_1200_THD

N_C224B
Cap_600_THD

N_C224B
Cap_300_THD

N_C234A
Cap_1200_THD

N_C234B
Cap_300_THD

N_C234C
Cap_300_THD

N_C214D
Cap_300_THD

N_C214D
Cap_300_THD

N_C214D
Cap_300_THD

N_C214D
Cap_300_THD
Sub-circuit 1
12-Pulse Front-End SCR Control - Set to 6-pulse operation, 5-MW, 85% P.F., starting at 60ms.
Sub-circuit 2
600-kvar Cap Bank with V/I THD Scopes

Sub-circuit 3 - I THD Scope
Sub-circuit 4 - Linear Load - Adjusted to Given P, Q

Sub-circuit 5 - Non-linear Load Input - Adjusted to Given P, Q
Linear Accelerator Substation 13-kV Bus

Results 1 - Va Thd

Results 2 - Va-n

Results 3 - IA
Results 6 - Ithd - Capacitor Currents - All Capacitor Locations - No locations with Ia THD over 35%

Results 7 - VThd - All capacitor locations - All under 5.0% Vthd
An approach to model high frequency behavior of large grounding systems into EMTP-RV

I. INTRODUCTION

GROUNDING system of a structure is the group of buried conductors whose goal is to provide an electrical connection to ground, for safety, functional grounding and/or fault protection systems. As an example, Figure 1 shows a classic ‘grid’ configuration for a substation and a less extended ‘4x3 loops’ configuration for a transport tower. We consider two terminals for the substation grid (Ia and Ib are the currents flowing from the network to the grounding system in terminals 1 and 2, respectively, and Ua and Ub are the relevant scalar potentials).

Figure 1 Tower and substation grounding.

Grounding systems play an important role for lightning protection of power systems and it should therefore be rigorously modeled when performing insulation coordination studies. For fast front transient phenomena as lightning, static lumped resistance models are not rigorous if the wavelength in soil is not quite greater then the total length of the underground conductors [1]. We will then show here how to take into account the frequency behaviour of such systems in the EMTP-RV.

II. GROUNDING SYSTEM FREQUENCY BEHAVIOR

A. Frequency behavior

We consider here that the behavior of the grounding system considered is linear (we neglect non linear phenomena such as the soil ionization). Then one can define the frequency impedance matrix \([Z(f)]\) which relates the current in each terminal of the grounding system to the corresponding scalar potential. As an example, for the grid presented in Figure 1, we have a 2x2 \([Z(f)]\) matrix:

\[
\begin{bmatrix}
V_a(f) \\
V_b(f)
\end{bmatrix} =
\begin{bmatrix}
Z_{11}(f) & Z_{12}(f) \\
Z_{21}(f) & Z_{22}(f)
\end{bmatrix}
\begin{bmatrix}
I_a(f) \\
I_b(f)
\end{bmatrix}
\] (1)

Line theory assumptions, on which most line models are based, are not rigorous for conductors non-isolated in soil. One should therefore use an alternative model (finite element, antenna theory, …) to compute \([Z(f)]\) values. We consider that one of the most accurate and effective approaches is the so-called Electromagnetic model, proposed by Dawalibi and Grecv in [2], and based on the Antenna theory. This model is used to compute \(Z_{11}(f), Z_{22}(f), Z_{12}(f)\) and \(Z_{21}(f)\) in (1) for several frequencies \(f\) on \([100Hz,1MHz]\). These discreet points are presented on Figure 2. Note that due to the symmetry of the system, we have: \(Z_{11}=Z_{22}\) and that the reciprocity principle involves: \(Z_{21}=Z_{12}\).
It can be seen that the large grounding grid has an inductive behavior: for high frequencies, the absolute values of $Z_{11}$ and $Z_{22}$ are higher than the low frequency ones. Concerning the mutual coupling between terminals, Figure 2 shows that it converges to zero for high frequencies, which means that high frequency transients on a terminal are not completely transmitted to the other one.

**B. Modeling of the grounding grid into EMTP-RV [3]**

The grounding system is modeled into EMTP-RV as a State-Space block (model developed by Hydro-Quebec/EDF partnership):

- the discreet frequency values of $[Y(f)]=[Z(f)]^{-1}$ obtained using the electromagnetic model are fitted to obtain rational approximations (several approaches have been presented for such a purpose [4][5]) of the form:
  \[
  Y_{n,m}(p) = \frac{I_n}{U_m} = \sum_{i=1}^{N_p} c_{n,m,i} p^{-a_{n,m,i}} + d_{n,m}
  \]
  \[p = j2\pi f\]  
  \[N_p\] the number of poles chosen for the fitting

- the obtained transfer functions are included in EMTP-RV using a state-space representation.

Following this approach, a complex grounding system with several terminals can then modeled by means of a unique block describing the relationship between currents and voltages at terminals. In the case of two terminals presented on Figure 1, these equations are:

\[
\begin{bmatrix}
Va(f) \\
Vb(f)
\end{bmatrix} =
\begin{bmatrix}
Z_{11}(f) & Z_{12}(f) \\
Z_{21}(f) & Z_{22}(f)
\end{bmatrix} *
\begin{bmatrix}
Ia(f) \\
Ib(f)
\end{bmatrix}
\]

Electromagnetic model results, for several frequencies $f$

\[
\begin{bmatrix}
\dot{X} = A \cdot X + B \cdot \begin{bmatrix}
Va \\
Vb
\end{bmatrix} \\
\begin{bmatrix}
Ia \\
Ib
\end{bmatrix} = C \cdot X + D \cdot \begin{bmatrix}
Va \\
Vb
\end{bmatrix}
\]

State space representation in EMTP-RV

$X$ is the state vector, and matrices $A$, $B$, $C$ and $D$, which define the transient behavior of the grounding system, can be obtained from the discrete values of mutual impedances $Z_{ij}$ computed with the Electromagnetic model.
III. INSULATION COORDINATION STUDY

As an application example, we consider again the system described on Figure 1, for which we will compute the transient voltages created on the transformer primary side when the substation portal support is struck by lightning. The simulation scheme is presented in Figure 4 [6].

We consider here two spans for the 225kV line; a long span (30km) is modeled at the left-end of the system to avoid reflection effects that would render less straightforward the discussion of the results.

- The transformer is modeled by 2.2nF capacitors between the phases and terminal b.
- Grounding systems of towers are loops and are not large, as a consequence they can be considered as static resistors on the frequency band [0Hz;1MHz]. We take here $R_t=10\ \Omega$, which is the mean value on French transmission network.
- Towers/support are modeled by 45m/10m CP lines with a characteristic impedance $Z_c$ of 150Ω.
- Ideal flashover switches are used to represent insulations towers/phases (850kV).
- Lightning surge arresters (ZnO’s) with an effective assigned voltage of 222kV and a lightning protection level of 550kV protect the portal.
- Grounding grid is either a State Space block (as described above), or a simple resistor $R=0.9\\Omega$, corresponding to the static resistance of the grid ($Z_{self}(100Hz)=Z_{mutual}(100Hz)$ on Figure 2).

![Figure 4](image)

Figure 4 – Model of the system presented in Figure 1.

When the portal support is struck, a part of the lightning current is circulating in the shield wire and terminal a. As a consequence, $V_a$ and $V_b$ increase, which may result in problems for the transformer.

We present in Figure 5 the lightning current ($I_f$), the scalar potential of terminals a and b ($V_a$ and $V_b$), and the output voltage of one phase of the transformer ($V_t$), when modeling the grid either with one resistor only (‘LF model’) and with the State Space block (‘State-space block’).

In this case, the values of $V_a$ and $V_b$ computed with both approaches (HF and LF) are quite different. With the LF approach, neglecting the inductive behavior of the grid (cf. $Z_{self}$ on Figure 2) leads to underestimate fast transients values of $V_a$. Concerning $V_b$, it is overestimated with LF model because we do not take into account the fact that high frequency transients on terminal 2 are not completely transmitted to terminal 1 (cf. $Z_{mutual}$ on Figure 2).
Concerning the stress on the transformer, both models of the grounding system of the substation grid lead to relatively low peak values for $V_t (<300\text{kV}, \text{or} \ 1.2 \text{ p.u.})$.

IV. CONCLUSION

We have shown how it is possible to model frequency behavior of complex grounding systems with several terminals for transient studies into EMTP-RV. From discreet results in frequency domain obtained using another model (or measures), we can obtain a simple ‘state space block’ model.

Considering a classical example, we have shown that neglecting the high frequency behavior of a large grounding system flowing a lightning current can lead to underestimate or overestimate the potential rise of its terminals. Although this approximation has, in general, few influences on coordination studies results, high frequency behavior should be taken into account if the potential of the grounding system are the variables of interest (as for some EMC studies).

BIBLIOGRAPHY


Support

TRAINING SUCCESS!

CEATI is pleased to report the success of two recent EMTP-RV training seminars: Perth, Australia, in April 2008 and Riyadh, Saudi Arabia, in June 2008. These events brought together engineers and students from around the globe.

We would like to take this opportunity to thank all those who contributed to events, in particular the instructors, and extend our congratulations to the students for their successful completion of the course.

Upcoming Training Opportunities

A four-day training seminar will be held from September 8-11, 2008 in Montreal, Quebec, Canada.

L’École Supérieure d’Électricité will be hosting a three-day training seminar from September 22-24, 2008, in Paris, France. This course will be conducted in French.

For more information regarding the above training opportunities, please visit our website: http://emtp.com/services/seminars.html

Other News

An EMTP-RV User Group meeting will be hosted by Électricité de France on September 25, 2008 in Clamart, France. This meeting is addressed to French-speaking users who wish to learn about the latest improvements in EMTP-RV, provide ideas for future developments and submit feedback on the current applications.

The EMTP-RV Toolbox Development Interest Group will hold its European meeting on September 30, 2008, in Lisbon, Portugal. As well, the regular meeting will take place in Montreal on October 10, 2008. The Toolbox Group is dedicated to developing software modules within the framework of EMTP-RV. For more information please contact Guillaume Paradis - Program Manager (guillaume.paradis@ceati.com).