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Determination of High-Frequency Current Distribution Using EMTP-Based Transmission Line Models with Resulting Radiated Electromagnetic Fields

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***Abstract*—Application of BPL technologies to existing overhead high-voltage power lines would benefit greatly from improved simulation tools capable of predicting performance - such as the electromagnetic fields radiated from such lines. Existing EMTP-based frequency-dependent line models are attractive since their parameters are derived from physical design *dimensions* which are easily obtained. However, to calculate the radiated electromagnetic fields, detailed current distributions need to be determined. This paper presents a method of using EMTP line models to determine the current distribution on the lines, as well as a technique for using these current distributions to determine the radiated electromagnetic fields.**

***Index Terms*—Transmission line, frequency dependency, modeling.**

I. Introduction

When overhead high-voltage transmission lines are used as the waveguide structure for broadband communications, interference caused by the radiated emissions from those lines becomes a matter of concern [1]. While traditional Power Line Carrier (PLC) in the 25-450 kHz range [2-3], has been used for years, present Broadband over Power Line (BPL) systems operate in the 2-80 MHz range [1,4]. This increase in frequency and corresponding decrease in wavelength corresponds to an increasing concern over radiated emissions.

Prediction of the radiated electromagnetic field from any antenna involves two steps: determination of the current distribution on the antenna, followed by determination of the resulting electromagnetic fields. Carrying out these steps when the ‘antenna’ is a realistic power system - with power lines and power system components such as transformers, capacitive banks, etc. - is a daunting task. In this paper we examine a novel two-step solution for the task.

Since this work involves two different types of modeling tools we first provide a fairly detailed background section. We examine present EMTP modeling approaches, as well as concerns that arise when using such modeling techniques at higher frequencies. We then present a unique method of applying EMTP-based transmission line models to determine the current distribution. This is followed by a description of how the radiated electromagnetic fields are determined from the current distribution. We then describe the particular test scenario used in this paper, which is followed by results and pertinent conclusions.

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II. Background

A. EMTP Modeling Approaches

Well known worldwide, EMTP-type software (e.g. ATP) has extensive features for modeling realistic power systems and has been successfully applied to determine PLC performance [5-6]. ATP is commonly used to determine terminal voltages and currents at characteristic power frequencies and for impulse and step response [7], although such software has not traditionally been used to determine detailed current distributions along the lines. To determine these currents using ATP we first consider the applicability and limitations of existing frequency-dependent EMTP line models which are based on physical design dimensions [8].

For higher frequencies or long lines, the two approaches that can be considered are a cascaded coupled-π model [3–Ch.11] and a distributed-parameter “long line” model. Development of presently used distributed-parameter transient transmission line models for this case are based on the “traveling wave model” “or telegrapher’s model” presented in many textbooks [3-Ch.9]. The representation for a single-conductor case is shown in Fig. 1. Note that distance (x) is measured from the receiving end toward the sending end.

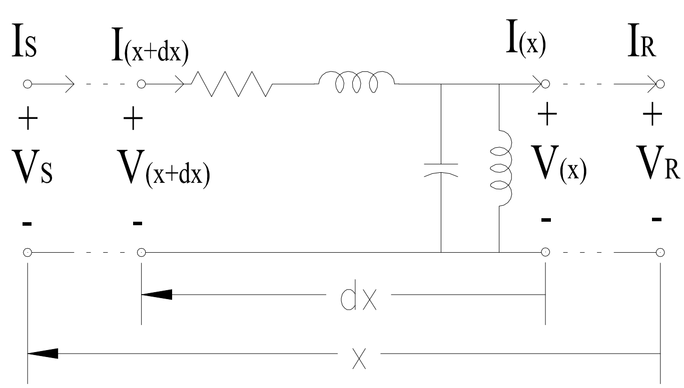

Figure 1. Telegrapher’s Model

For a general multi-conductor case, the basic equations are

$$-\frac{\partial V}{\partial x} = [Z]I \quad \text{and} \quad -\frac{\partial I}{\partial x} = [Y]V \ , \tag{1}$$

where V and I are the vectors of node voltages and line currents at a distance x from the receiving end of the multiple conductor transmission line. Z is the matrix of coupled series impedances of the conductors for an incremental length, and Y is the matrix of coupled shunt admittances for that same length. Details of solution are given in [3] and in references [9-13]. The equations from (1) can be combined to form

$$\frac{\partial^2 V}{\partial x^2} = [Z][Y]V \quad \text{and} \quad \frac{\partial^2 I}{\partial x^2} = [Y][Z]I \ , \tag{2}$$

where

$$Z_{ij} = R_{ij} + L_{ij}\frac{\partial}{\partial t} \quad \text{and} \quad Y_{ij} = G_{ij} + C_{ij}\frac{\partial}{\partial t} \, . \tag{3}$$

Modal transformations can be used to transform the "phase domain" equations into a set of decoupled "modal domain" equations which can simplify the mathematics for model implementation:

$$V = [T_v]V_m \quad \text{and} \quad V = [T_i]I_m \tag{4}$$

where V_m and I_m are modal voltages and currents, and $[T_v]$ and $[T_i]$ are the voltage and current transformation matrices which are also used to transform Z and Y into their decoupled modal forms Z_m and Y_m.

$$-\frac{\partial V_m}{\partial x} = [T_V]^{-1}[Z][T_i]I_m = [\mathrm{Z_m}]I_m \tag{5}$$

$$-\frac{\partial I_m}{\partial x} = [T_i]^{-1}[Y][T_V]V_m = [\mathrm{Y_m}]V_m \tag{6}$$

ATP utilizes Karrenbauer's Transformation, which is easily expanded to an arbitrary number of phases:

$$T = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & (1-M) & \ddots & \vdots \\ \vdots & \ddots & \ddots & 1 \\ 1 & \cdots & 1 & (1-M) \end{bmatrix} , \tag{7}$$

where M is the number of phases.

$$T^{-1} = \begin{bmatrix} 1 & \cdots & \cdots & 1 \\ \vdots & -1 & & \\ \vdots & & \ddots & \\ 1 & & & -1 \end{bmatrix} \tag{8}$$

The physical representation of this for a 3-phase set of conductors is given by Figs. 2-4.

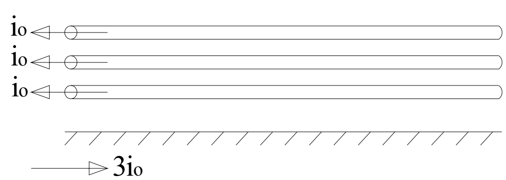

Figure 2. Mode Zero

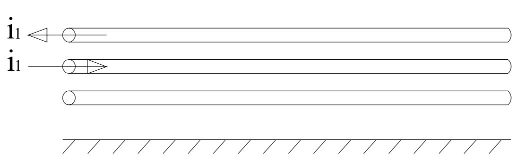

Figure 3. Mode One

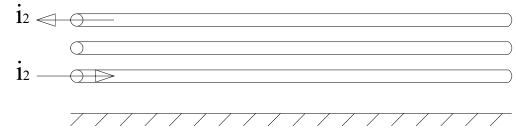

Figure 4. Mode Two

Convolution methods are used to convert the frequency-domain solution to a time-domain equivalent that can be implemented in time-domain simulation programs like EMTP. Errors in this approach are due to the fact that the solution is only valid for the frequency that the model was developed [9-10]. Improvements have been made by applying frequency-dependent weighting functions to the convolution [11-12], by developing improved frequency fitting techniques [12], and by developing the model directly in the phase domain and thus avoiding modal transformations [13]. More recent advancements include improved frequency fitting techniques [14]. In any case, it is desirable to confirm that the line model being implemented is valid within the range of frequencies to be simulated. The foster equivalent shown in Fig. 5 is the basis for the frequency-dependent Z.

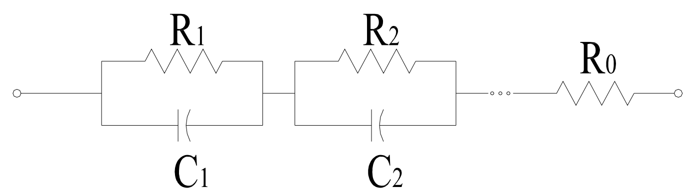

Figure 5. Foster Equivalent

Fig. 6 shows the basic representation of each end of the multi-phase Marti model [12]. Behaviors at one end manifest themselves at the other end after the appropriate propagation time delay.

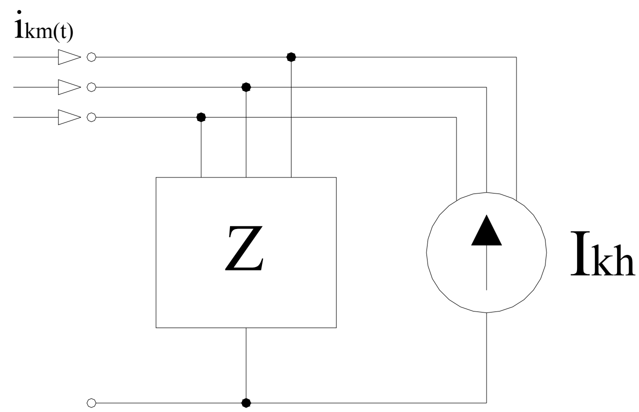

Figure 6. Marti Model

B. Electromagnetics-based Models

To accurately predict the performance of any natural phenomena (such as energy propagating on overhead transmission lines) one must pay attention to the limitations of the prediction model being used. As mentioned above, programs like EMTP are based on the "traveling wave model" "or telegrapher's model". As observed by Paul and others [15-18], one of the underlying assumptions for this model is that the electromagnetic fields surrounding the transmission line structure are TEM (transverse electromagnetic) fields – i.e., that the electromagnetic fields are perpendicular to the direction of propagation (or lie in a plane transverse to direction of propagation). For the model to be strictly valid, we assume (a) the conductors are parallel to each other and to the direction of propagation, (b) they are perfect conductors (i.e., no resistance) and (c) the conductors have uniform cross section along the line axis. In addition, (d) the region surrounding the conductors is assumed homogeneous (although it can be lossy). It can also be shown (at least for two-conductor lines) that under the TEM assumption, the currents in the two conductors must be equal in magnitude and opposite in direction – i.e., that for any cross-section of the line, the total current flowing in the conductors must be zero [15,19]. It would appear that very few 'real life' transmission lines satisfy all of these criteria. In fact, almost all conductors have some resistive loss, lie over an imperfect ground (so they are immersed in an inhomogeneous material) and are not perfectly uniform in cross section. Although this is true, when we are examining parallel transmission lines operated at a frequency for which the cross-sectional dimensions of the line are much less than a wavelength, solution of the transmission line equations gives significant contribution to the fields and the resulting terminal voltages and currents. Such solutions are commonly referred to as 'quasi-TEM' [15] or 'quasi-static' [17] solutions. A vast body of research has been conducted evaluating when such solutions are accurate [20-22]. Olsen [17] points out that that when the height of transmission line is small compared to the wavelength in free space that the quasi-static approximation can be made, with the resulting solutions being identical to those derived by Carson [24]. Although these approximations may be valid at power frequencies, the situation changes when considering BPL frequencies when cross-sectional dimensions of the line are no longer a fraction of a wavelength.

To evaluate whether or not a given model will give accurate results one must not only ask what assumptions might be violated, but also what the results will be used for. For example, in the case of a transmission line if the desired result is to determine the terminal voltages and currents to evaluate load flows, etc., quasi-static solutions obtained from solving the transmission line equations might be perfectly acceptable. If, however, one wants to determine the electromagnetic fields radiated from the transmission lines, the error resulting from solutions based on the transmission line equations might be unacceptable. The reason is that the currents obtained from solution of the transmission line equations are truly the transmission mode (or differential line mode) currents [15-16] – i.e., currents that are flowing in opposite directions.

When the TEM assumptions are satisfied, these are the only currents that exist. When this is not the case, however, antenna mode (or common mode) currents can also exist [15-16]. These are currents that are flowing in the same direction on the lines. For most power transmission line problems, the transmission line currents are dominant, so that if one wants the terminal currents and voltages, approximate results based on transmission line theory may be perfectly adequate. It turns out, however, that in the case of radiated fields antenna mode currents tend to be very significant – even if they are much smaller in magnitude than transmission line mode currents [25-26]. According to Paul [15] and Tesche [16] the reason is because the radiated fields from transmission line currents tend to subtract but those from antenna mode currents add.

To address the concern of interference potential from BPL signals propagating on power lines, researchers have turned to a number of strategies to predict the antenna mode currents (from which the resulting fields can be determined). One method is to use techniques commonly employed by those working with antennas and with other high-frequency applications of electromagnetics. A number of methods are available in the computational electromagnetics area, including the moment method, the finite element method, the finite difference method, and a host of others [16, 27-29]. Recent papers examining this issue have used a variety of techniques to analyze this problem [30-32].

One of the difficulties encountered using high-frequency methods to examine the radiated fields from practical power lines lies in modeling the multitude of components in a practical power system (i.e., transmission lines, transformers, capacitive banks, etc.). High-frequency techniques tend to work well for things like the transmission lines themselves (since they can be modeled as wires), but get cumbersome when other power system components are included in the model. Programs like EMTP-ATP, however already have lumped models for most of the power system components available. We now turn to examining how to use these models to determine the current distribution.

III. Development of EMTP-ATP Line Model

A. Modeling Needs

Distributed line currents and voltages are of particular interest in simulation of line performance for communications. These values are particularly important for determining the radiated fields, which are also of interest. The robust and flexible nature of EMTP-type software (e.g. ATP) makes it an ideal platform for carrying out such work. The power system modeling features of ATP are extensive and are used across the globe for time-domain analysis. An area that has yet to be explored, however, is in high resolution modeling of distributed currents along transmission lines. A powerful "Line & Cable Constants" (LCC) feature of ATP is used for building transmission lines and for calculating impedance matrices. For short-line modeling, the pi approximation has been widely used. For the characteristic power frequencies there is no need to obtain highly detailed current distributions along the lines. In order to study the effects of PLC at much higher frequencies, however, the decreasing wavelengths make these highly detailed models increasingly important. The resolution of current distributions must befit the frequency being used in order to accurately calculate the radiated fields. A cascaded-pi approach is capable of meeting these needs.

B. Implementation of Cascaded Models

Transmission lines have uniformly distributed parameters while pi models are lumped parameter approximations. The pi sections modeled in ATP can be used in a cascaded approach to incrementally define the line parameters. Fig. 7 demonstrates the use of cascaded pi line sections to approximate a distributed parameter line.

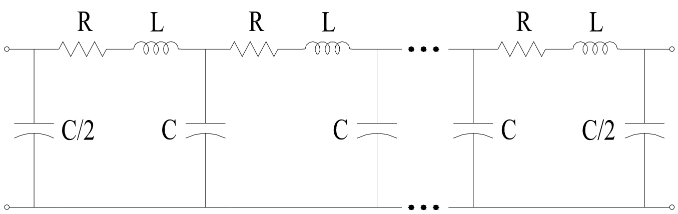

Figure 7. Cascaded Pi Representation

As mentioned before, it is necessary to have highly detailed line models when studying effects of higher frequencies and when dealing with increasingly small wavelengths. By shortening the line segments in the LCC modules of ATP, a finite number of short, cascaded pi line sections can more closely approximate a distributed parameter model. By breaking down the pi model, the line currents can be obtained for each incremental pi section. The minimum number of cascaded pi sections needed to accurately represent the line is determined by

$$f_{max} = \frac{N*\nu}{8*\ell} \ , \tag{9}$$

where f_{max} is the maximum of the desired frequency range, ℓ is line length (km), and ν is the propagation speed (km/s). The number of cascaded pi sections needed is thus linked to the upper limit of the desired frequency range. As the desired frequencies become very high, an obvious limitation of the cascaded approach is that a very high number of circuit elements are needed. Since the distribution of line currents is also in question, the number of simulation outputs also becomes very high. For these reasons, ATP requires a special application file designed to accommodate the higher number of circuit elements. This version, titled 'gigmingw' is readily available through the European EMTP/ATP Users Group. Because distributed line voltages and currents can be directly obtained by this method, calculation of the associated electromagnetic fields can next be achieved.

IV. Development of Radiation Model

The Electromagnetics Interactions Generalized (EIGER) code was developed by the University of Houston, Sandia National Laboratory, and Lawrence Livermore National Laboratories. This three-dimensional, boundary element, frequency domain, code allows the computation of electric and magnetic fields from arbitrary sources built with wires, patches, and surfaces. EIGER is freely available from Sandia National Laboratory (www.sandia.gov). Ideally, radiated fields from BPL sources could be predicted entirely from EIGER. However, as previously stated, transmission lines contain passive and active devices for power distribution control which cannot easily be built in EIGER; transformers being one example. Therefore, the EIGER source code was modified to accept the external ATP current distribution. Without this modification, the user would be required to accept a current distribution from a voltage or current source and approximate transmission line devices with lumped parameters; the result would be decreasing accuracy with increasing frequency.

Given a BPL current distribution calculated from ATP, the complex current is interpolated and substituted for the EIGER transmission line model current file (*.mnh). Executing the modified version of EIGER results in the ATP current distribution, EIGER model geometry, and terrain information being numerically combined into a Green's Function [34] which is then used to calculate the BPL radiated electric and magnetic fields. Using EIGER is beneficial for several reasons; the field predictions are valid into the GHz range, one can account for the presence of a lossy and inhomogeneous earth, and geological terrain, which might otherwise alter predicted BPL fields, can also be included in the EIGER model as dielectric bodies.

V. Test Scenario

A. Line Description

A test-case transmission line was identified to demonstrate the usefulness of the method for obtaining distributed line currents and radiated fields. An isolated 5 km, 3-conductor non-transposed line was chosen for study. The flat terrain is a homogeneous ground characterized by $\varepsilon = 8.0 + j1.0$ [34]. Conductor spacing is realistically defined for a standard distribution tower structure. Using the center-pole as a reference, phases A and B are left of center by 1.2192 and 0.3048 meters respectively. Phase C is right of center by 1.2192 meters. The conductors have a height of 9.5 meters with 0.75 meter sag and 0.03576 Ω/km dc resistance. The line was terminated with a small, wye-configured load of 10 Ω for each phase. A current source placed at the sending end supplied a 3-phase sinusoidal current as the injected signal. A frequency scan was then used to determine the current distributions for every 5 meters, with 1,000 pi sections in total.

VI. Results

A. Current Distribution from ATP

Using the line description from section V, the distributed line currents were obtained in ATP. Shown in Fig. 8 is the distributed current along one conductor as a function of line distance for a 500 kHz injected signal. Note that the figure shows magnitudes only, and that a large source current was used for this demonstration. Though BPL systems would typically use smaller signals, the process for determining the currents and resulting fields will be the same as in this example. Additionally, while BPL frequencies are typically in the tens of MHz, the authors wish to only describe the process in this manuscript, using a lower frequency.

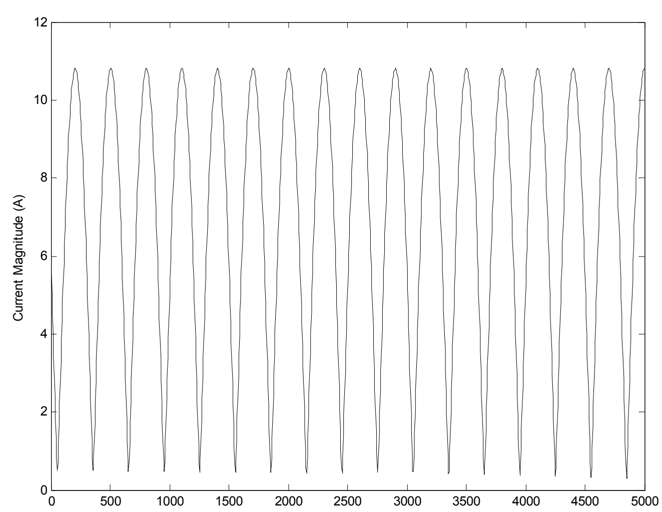

Figure 8: 500 kHz ATP current distribution along line

B. Radiated Fields from EIGER

The 5 km transmission line from Section V is built into the EIGER model. An ASCII file of the real and imaginary transmission line current as function of line distance, and for each phase, is then created from ATP at a frequency of 500 kHz. We do not calculate far-field patterns from EIGER, but rather a series of near field points, due to the large wavelengths at these frequencies; about 100 meters from ACSR wire with velocity of 0.33 the speed of light at 1 MHz [35]. The fields from this test case are arbitrarily calculated at 50 meters above the transmission line in a constant altitude plane, although fields can be calculated in any volume. Fig. 9 illustrates the results for the amplitude of the vertical magnetic field (the black line represents the transmission line). Note that while Fig. 8 shows that impedance mismatches at the transmission line boundary sets up a standing wave for the current distribution with the number of nodes proportional to the frequency, the radiated fields incorporate the radiation efficiencies of the transmission lines. In essence, the current distribution and radiation efficiency are convoluted.

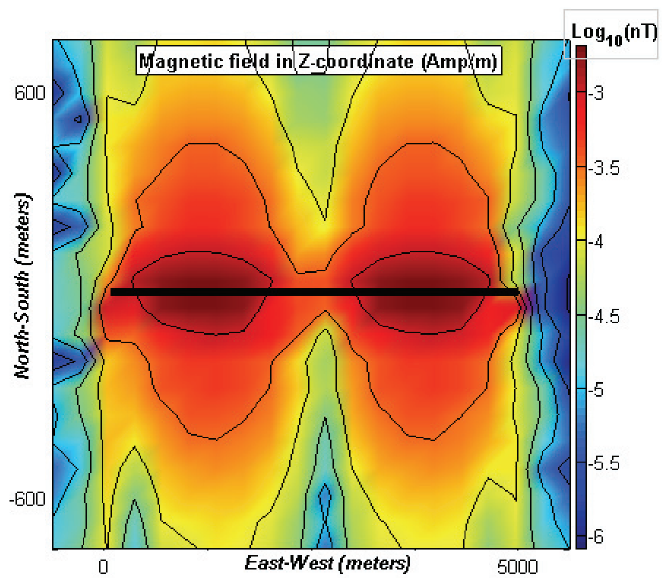

Figure 9. Magnitude of radiated vertical magnetic field at altitude of 50 m.

VII. Conclusions and Recommendations

Radiation from BPL systems has the potential of causing interference and radiation losses from BPL systems can be significant. In order to predict both of these, EMTP-ATP is used to determine the current distribution of a transmission line. This current distribution is then overlaid onto the electromagnetic EIGER model of the physical transmission line to determine the radiated fields of a BPL system. This two-fold system is beneficial because EMTP-ATP can accurately model power electronic devices and control schemes and the components found in power systems (e.g. power transformers, instrument transformers, communication couplers, etc.) which cannot be ignored in these studies. Given this current distribution, EIGER can account for the inhomogeneity commonly found in the earth as well as using dielectric bodies to approximate terrain effects. While EIGER is valid into the microwave region (GHz), EMTP-ATP capabilities have not been validated for such high frequencies. Future work will examine this limitation and attempt to extend EMTP-ATP into higher frequency regimes.

VIII. Acknowledgment

The authors gratefully thank Ben Fasenfest at Lawrence Livermore National Laboratory for EIGER modifications and helpful discussions. Hans Kristian Hoidalen at the Norwegian Institute of Science and Technology is thanked for his assistance with ATPDraw Line Constants interface to ATP.

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X. BIOGRAPHIES

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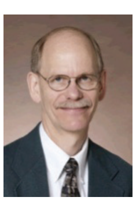
Dr. Mork is a member of ASEE, NSPE, and Sigma Xi. He is a Registered Professional Engineer in the states of Missouri and North Dakota.



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