Tribute to Prof. Akihiro Ametani for Contributions to Research on Power System Transients

H. Xue, J. Mahseredjian, M. T. Correia de Barros

***Abstract*--This paper presents a summary of significant contributions on research on power system transients performed by Prof. Akihiro Ametani at Polytechnique Montréal, Canada. The contents of the paper are based on the results published by Prof. Ametani, his former colleagues and students at Polytechnique Montréal. The paper involves three parts: theoretical innovation and implementation, field measurements and numerical electromagnetic analysis. The major contributions are related to line/cable modeling. The important impact of each part is also highlighted in this paper.**

***Keywords*: Electromagnetic transients, overhead lines, underground cables, field measurements, MoM, FDTD.**

I. INTRODUCTION

THIS paper presents a summary and review of significant research contributions conducted by Prof. Akihiro Ametani during his stay at Polytechnique Montréal in Canada.

Prof. Ametani is very well-known for his research and development contributions in power system transients [1]-[4]. He started his academic and professional life in 1970 as a Ph.D. researcher with Prof. Martin Wedepohl of University of Manchester. In the past several decades, Prof. Ametani dedicated to understanding fundamental phenomena of wave propagation in various transmission systems exposed to transient conditions, i.e. energization, fault, switching and lightning. His solid knowledge and thorough understanding of the subject allowed him to propose innovative techniques to deal with modeling of transmission lines and cables, and further led him to develop the renowned Cable Constants code which has been widely used in electromagnetic transient type (EMT-type) simulation software since the beginning of 1980s [2], [5]-[7]. Prof. Ametani also deeply engaged into research of numerical electromagnetic methods which can be used as full wave solutions for analysis of electromagnetic transients in complicated structures [8].

As an invited professor, Prof. Ametani was in the Department of Electrical Engineering at Polytechnique Montréal between 2014 and 2018. During these five years, Prof. Ametani participated intensively in the Industrial Research Chair named “Multi-Time-Frame Simulation of Transients for Large-Scale Power Systems”, led by Prof. Jean Mahseredjian. He has successfully supervised 3 Ph.D. students [9]-[11] and 1 Master student [12] together with Professors. Mahseredjian, Correia de Barros and Kocar. Moreover, Prof. Ametani maintained strong research collaboration with academic and industrial partners, i.e. Ecole Polytechnique Fédérale de Lausanne (EPFL), Doshisha University, Cardiff University, University of Lisbon, Réseau de Transport d’Electricité (RTE), Hydro-Québec, National Grid, Electricité de France (EDF) etc. In addition, he served as a steering committee member and key organizer for International Conference on Power Systems Transients (IPST), International Symposium on EMC and Transients in Infrastructures - International Student Session (ISET-ISS), and IEEJ High Voltage Engineering Technical Meeting. Those conferences were successfully organized in Croatia, South Korea, France, Japan, Vietnam and Canada, respectively.

On the 4th of January 2022, Prof. Ametani passed away in Nagasaki, Japan. This paper summarizes his significant contributions as a memory on his great passage at Polytechnique Montréal. Therefore, the contents of this paper are based on the selected results published by him, his former colleagues and students at Polytechnique Montréal. The paper involves three major parts: theoretical innovation and implementation [13]-[23], field measurements [24]-[28] and numerical electromagnetic analysis [29]-[35].

II. THEORETICAL INNOVATION AND IMPLEMENTATION

The contribution of this section focuses on theoretical innovation on determination of parameters for overhead lines and underground cables. The classical and extended transmission line (TL) approaches are defined based on expressions of series impedance and shunt admittance of transmission lines and cables. By adopting various methods, the fundamental understanding of high frequency characteristics of overhead conductors and cables is investigated. Also, several new formulas are derived for evaluation of earth-return parameters on overhead lines and underground cables. The research carried out by this section serves as a cornerstone for the development of a new line and cable data calculation tool.

A. Development of Extended Transmission Line Approach

In general, the calculation of frequency-dependent series impedance and shunt admittance of lines (or cables) has the following expression [1]:

$$\mathbf{Z} = \mathbf{Z_i} + \mathbf{Z_e} \tag{1}$$

$$\mathbf{Y} = j\omega \mathbf{P}^{-1} \tag{2}$$

where $\mathbf{Z_i}$ is the internal impedance, $\mathbf{Z_e}$ is the earth-return

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impedance matrix. The potential coefficient matrix $\mathbf{P}$ is defined as

$$\mathbf{P} = \mathbf{P_i} + \mathbf{P_e} \tag{3}$$

with $\mathbf{P_i}$ and $\mathbf{P_e}$ being the internal and earth-return potential coefficient matrices, respectively.

In [1] and [10], equations (1) and (3) are designated as extended TL approach. Carson's or Pollaczek's earth-return impedance with constant space or insulator potential coefficient is called classical TL approach.

B. High Frequency Wave Propagation and Transients on Overhead Lines or Cables

Fig. 1 shows high frequency characteristics of attenuation constant for a single overhead conductor. The details on parameters can be found in [13], [14]. It should be noted that an overhead conductor can be viewed as a special cable without insulator [7]. In the figure, NEC represents Numerical Electromagnetic Code which is based on the Method of Moments (MoM).

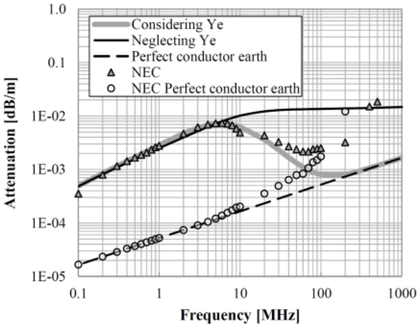


Fig. 1 Attenuation constant, single overhead conductor at high frequency [13],[14].

It is clear that the attenuation is the same for the results produced by classical TL (neglecting $\mathbf{Y_e}$) approach, extended TL approach (considering $\mathbf{Y_e}$) and NEC in a lower frequency region. At a certain frequency, the attenuation starts to decrease if earth-return admittance $\mathbf{Y_e}$ is included in the calculation of TL approach, and the same behavior is observed for NEC. Thus, the earth-return admittance due to an imperfectly conducting earth affects the attenuation on a conductor.

When a lossy earth is considered, the attenuation starts to decrease at the critical frequency f_c and the Sommerfeld - Goubau (surface wave: TM mode) propagation is completed at f_s. In the frequency region $f_c < f < f_s$, transition occurs between quasi-TEM mode and surface wave mode [13], [14].

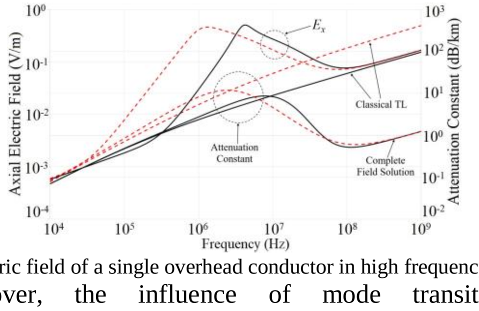
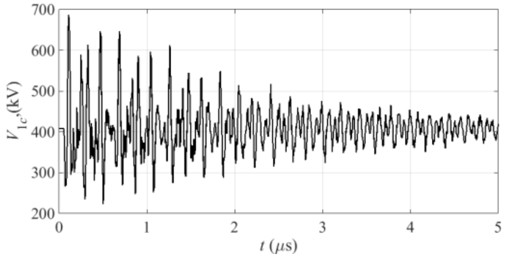


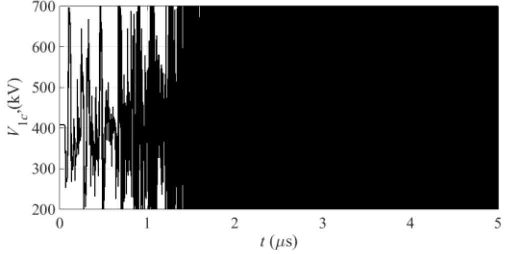
Fig. 2 Electric field of a single overhead conductor in high frequency [15].

Moreover, the influence of mode transition on electromagnetic fields is investigated in [15] using complete field solution. As shown in Fig. 2, it further proves the mode transition of overhead conductors at high frequency.

Based on the above fundamental research on high frequency phenomena, the extended TL approach has been implemented to study very fast transients (VFTs) in gas - insulated substation (GIS) using an EMT-type simulation software (EMTP) [36] and the wideband (WB) cable model [37]. The GIS can be modeled by an overhead cable. First of all, the numerical instability of the WB model for simulation of GIS is avoided, as shown in Fig. 3 [16]. The extended TL approach significantly improves numerical fitting for the WB model.



(a) Extended TL approach



(b) Classical TL approach

Fig. 3 Instability of EMT simulation of core voltage for GIS [16].

Next, finite-difference time-domain method (FDTD) is adopted to further validate the results of VFT simulation using EMTP and WB model, as shown in Fig. 4 [17], [18]. The results obtained by two methods show reasonable agreement.

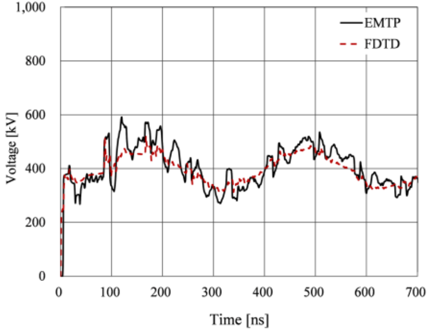


Fig. 4 Core voltage at receiving end of GIS [18].

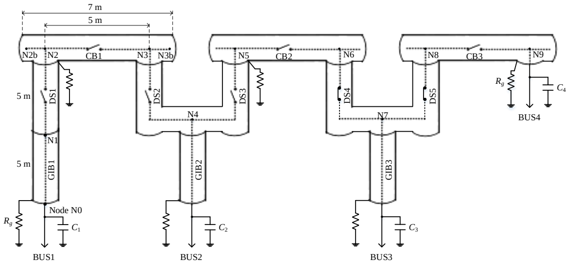


Fig. 5 Layout of a 500 kV GIS [19].

Then, a thorough investigation of VFT on a practical 500 kV GIS by adopting extended TL approach is performed in reference [19]. The layout of the 500 kV GIS is illustrated in Fig. 5.

The investigation in reference [19] contributes to further understanding of VFT, and simulation results can be used as reference of estimating the VFT overvoltages, oscillating frequency and optimum pipe grounding for electromagnetic compatibility related recommendation and standards in GIS.

C. *Generalized Formulation of Earth-Return Parameters for Lines and Cables*

EMT-type simulations of transmission systems require accurate calculations of earth-return parameters. Earth-return impedance and admittance are significantly influenced by the characteristics of earth models.

1) *Overhead lines*

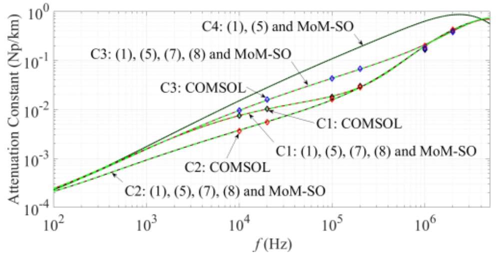
In reference [20], [21], a generalized and exact formulation (EF) of earth-return impedance and admittance of overhead lines above a non-homogenous earth is derived. Considering several remarkable advantages, such as satisfactory accuracy, simplification of formulas and high computational efficiency, an equivalent homogeneous earth method (EHEM) is also developed [20] to evaluate earth-return parameters of overhead lines above a non-homogenous earth, and it has

$$Z_{eij} \approx \frac{j\omega\mu_0}{2\pi}\left[\ln\left(\frac{D_2}{D_1}\right)+2\int_0^{+\infty}\frac{e^{-s\left(h_i+h_j\right)}\cos\left(sy_{ij}\right)}{s+\sqrt{s^2+\gamma_{eq}^2}}ds\right] \qquad (4)$$

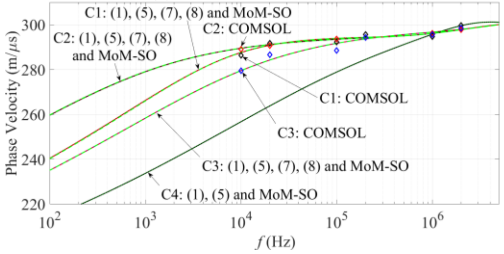
$$P_{eij} \approx \frac{1}{2\pi\varepsilon_0}\left[\ln\left(\frac{D_2}{D_1}\right)+2\int_0^{+\infty}\frac{e^{-s\left(h_i+h_j\right)}\cos\left(sy_{ij}\right)}{\frac{\gamma_{eq}^2}{\gamma_0^2}s+\sqrt{s^2+\gamma_{eq}^2}}ds\right] \qquad (5)$$

where γ_{eq} is the newly derived equivalent propagation constant of an *N*-layer earth and the details are given in reference [20].

Fig. 6 shows the calculated propagation constants of earth-return mode by adopting EF (equations (1) and (5) in Fig. 6), EHEM (equations (7) and (8) in Fig. 6), MoM-SO and Mode Analysis of Finite Element Method (FEM) in COMSOL [20].



(a) Attenuation constant



(b) Phase velocity

Fig. 6 Propagation constant of earth-return mode for C1: 4-layer earth, C2: 3-layer earth, C3: 2-layer earth and C4: homogenous earth [20].

It should be noted that EF and EHEM methods can be regarded as extended TL approach since full expressions of (1) and (3) are used. The influence of multi-layer earth on attenuation constant of earth-return mode is observed between 100 Hz and 5 MHz. Also, the propagation constants obtained by different methods are well validated by each other.

2) *Underground cables*

A generalized formulation of earth-return impedance and potential coefficient of underground cable has been proposed in [22], and it has the following formulas.

$$Z_{eij} = \frac{j\omega\mu_0}{2\pi}\left[K_0\left(jk_e d_{ij}\right)-K_0\left(jk_e D_{ij}\right)+2\Delta_4^{\mathrm{QT}}-2k_e^2\Delta_6^{\mathrm{QT}}\right] \qquad (6)$$

$$\begin{aligned} P_{eij} = &\frac{j\omega}{2\pi\left(\sigma_1+j\omega\varepsilon_1\right)}\Big[K_0\left(jk_e d_{ij}\right)-K_0\left(jk_e D_{ij}\right) \\ &+2\Delta_5^{\mathrm{QT}}-2k_e^2\Delta_6^{\mathrm{QT}}\Big] \end{aligned} \qquad (7)$$

where the details can be found in [22].

Fig. 7 shows transient sheath voltage at the receiving end of a three-phase single core cable [22]. A noticeable difference between classical and extended TL approaches is observed. The extended TL approach shows a higher damping effect due to earth-return admittance in (3).

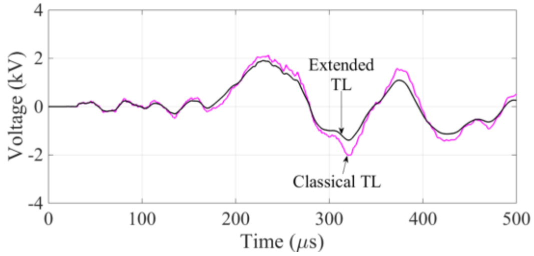


Fig. 7 Sheath voltage at the receiving end of a cross-bonded cable [22].

3) *Improved MoM-SO Method*

In reference [23], a modified Green function of earth-return for multi-phase overhead lines is derived. The proposed Green function (equation (17) in Fig. 8) can be used to avoid possible numerical instability in the existing technique [23] for evaluation of parameters of transmission lines and cables.

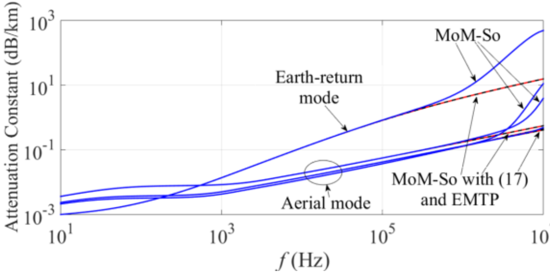


Fig. 8 Modal attenuation constants evaluated by different methods [23].

III. FIELD MEASUREMENTS

This section presents a brief review for three significant field measurements and their simulation validations in references [24]-[28]. The measurements are related to high voltage power cables in France, Japan and UK. The modeling techniques validated and discussed in this section can be applied to any EMT-type simulation tool for the study of cable transients.

A. *A Surge Test of Cable*

In 2014, A surge test on a new cable installed in the southeast of France between the regions of Boutre and Trans-en-Provence [9], [24], [25] has been performed. This is a 225 kV XLPE underground cross-bonded cable with 64 km of length and it is one of three underground links that has been built to reinforce the connection of the PACA region (Provence-Alpes-Côte d'Azur) to the French grid, previously fed through a single 400 kV overhead link [25].

The main objective of the test is to improve knowledge on the implemented system and validate cable modeling for transient studies. The configuration and parameters of the cable are illustrated in Fig. 9, with details given in [24].

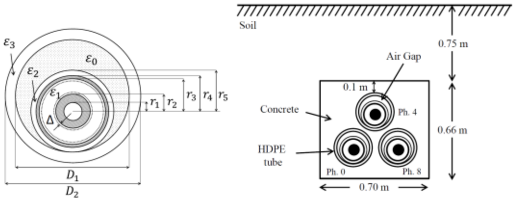
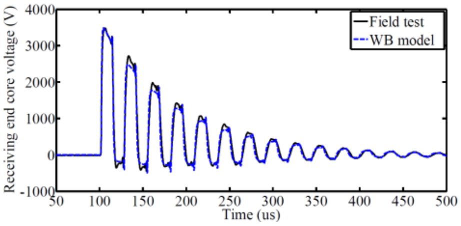


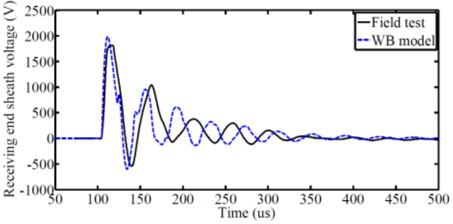
Fig. 9 Layout of RTE 225 kV cable system [24].

The field tests on both minor and major sections are performed separately for coaxial, inter-sheath and earth-return modes [24]. Fig. 10 shows a typical comparison of results obtained by field measurement and transient simulation using the WB model. The details of cross-bonded structure and set up of test circuit in different modes are given in [24].

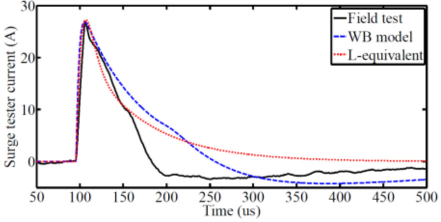
It is clear that the simulation results are in sufficiently good agreement with field test results. The most important differences are observed for the excitation of the earth-return mode, which is highly dependent on frequency, humidity and temperature, and for which the actual test setup conditions are more difficult to identify.



(a) Core voltage at receiving end, co-axial mode



(b) Sheath voltage at receiving end, inter-sheath mode



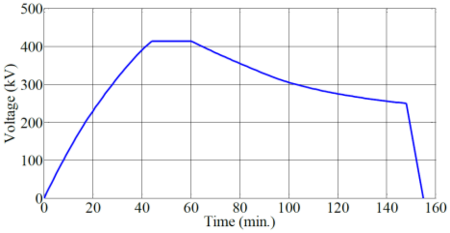
(c) Sheath current at sending end, earth-return mode

Fig. 10 Field measurement and simulation results for different modes, minor section of cable [24].

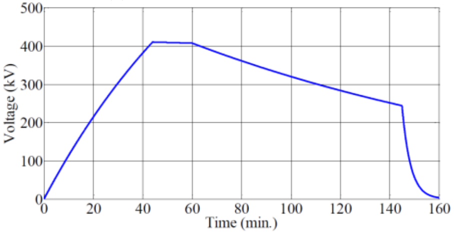
B. A Study of Cable Discharge

Recently, the cable discharging phenomenon has received new consideration for utilities when performing AC/DC tests, during maintenance works, and more recently when switching cables for grid voltage control. Considering the facts, a thorough study of cable discharge has been investigated based on field measurements of 275 kV pressurized-oil-filled (POF) cable, analytical calculations and simulations [26].

As shown in Fig. 11 and Fig. 12, the discharge time constants observed in the two field tests on 275 kV POF cables, range from 1.5 to 3.5 hours [26]. The time-domain simulations show good agreement with measurements.

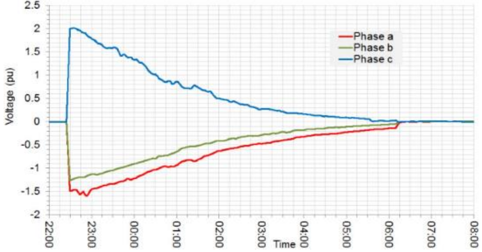


(a) Field measurement result

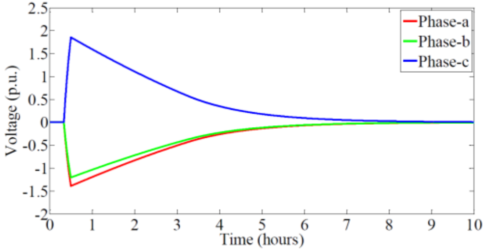


(b) Simulation result

Fig. 11 Discharging results of a 275 kV pipe-type POF cable [26].



(a) Field measurement result



(b) Simulation result

Fig. 12 Discharging results of a 275 kV POF cable [26].

C. A Validation of Cross-Bonded Cable Model

Cross-bonding and grounding of sheaths are used to improve the performance of long high voltage cable systems by reducing sheath currents, thus improving cable ampacity, and by reducing sheath voltages for preventing breakdown of cable insulation.

The influence of full discrete and homogeneous models of cross-bonded cable on EMT-type simulations are systematically studied in references [27], [28]. The RTE 225 kV cross-bonded cable with 17 major sections for a total length of 64 km has been adopted into the study. The field test layout is given in Fig. 13. As shown in Fig. 14, the simulated core voltage results have been validated with both full discrete and homogeneous models of major sections. The effectiveness of full discrete and homogeneous models of cross-bonded cable has been further confirmed.

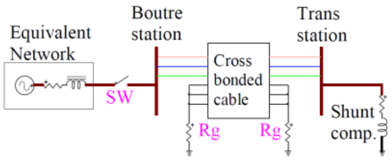
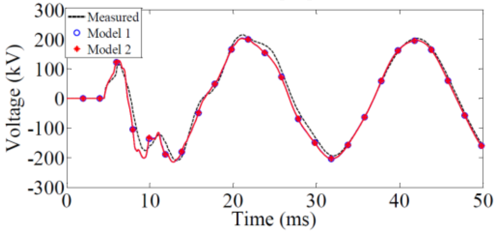
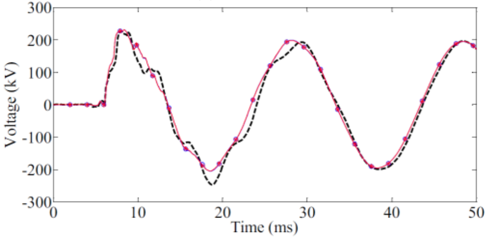


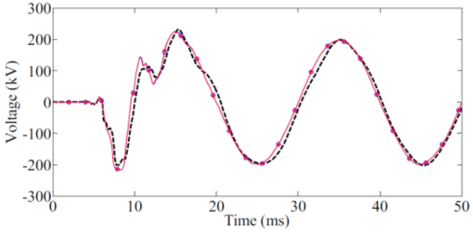
Fig. 13 Circuit of field test and simulation [27].



(a) Phase A



(b) Phase B



(c) Phase C

Fig. 14 Field measurement and simulation results for core voltages at sending end of cable, Model 1: full discrete, Model 2: homogeneous [27].

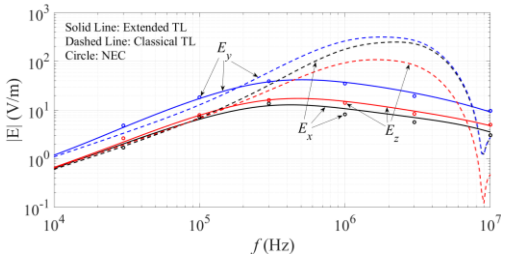
IV. NUMERICAL ELECTROMAGNETIC ANALYSIS

Numerical electromagnetic analysis can be used to deal with the study of electromagnetic transient and compatibility on highly complicated structures. This section concludes research performed by MoM and FDTD based techniques. It involves validation of extended TL approach and study of lightning induced overvoltage in distribution systems.

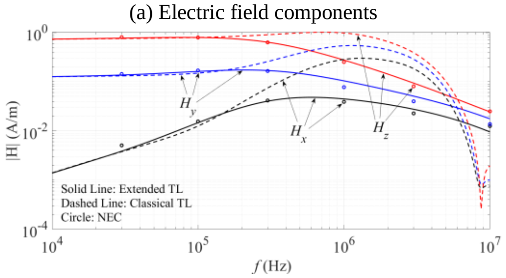
A. *MoM based Technique*

The extended TL approach has become a significant improvement for development of new line and cable data calculation tools. Therefore, a solid validation of the extended TL approach is crucial for the EMT society.

In references [29], [30], a generalized formulation for electromagnetic fields generated from a multi-phase underground cable with and without consideration of termination is derived. Then, electromagnetic fields of energized cable are calculated by classical and extended TL approaches, and the results are thoroughly validated by NEC. As shown in Fig. 15 and Fig. 16, the electromagnetic field components evaluated by extended TL approach show good agreement with the results obtained by NEC. More details are given in [29], [30].

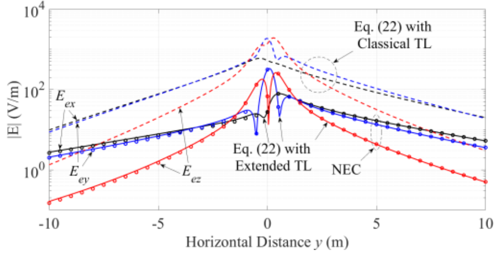


(a) Electric field components

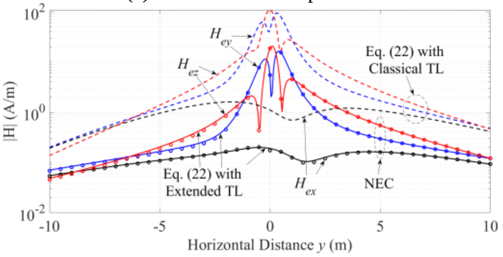


(b) Magnetic field components

Fig. 15 Electromagnetic field components calculated by various methods as function of frequency [29].



(a) Electric field components



(b) Magnetic field components

Fig. 16 Lateral profiles of electromagnetic field components calculated by various methods [30].

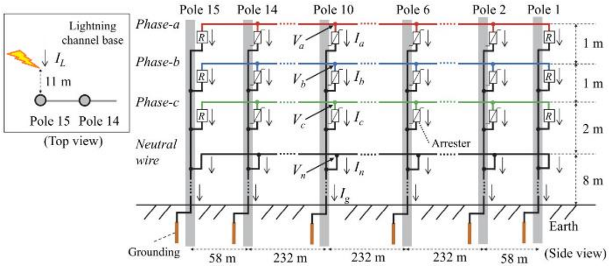
B. *FDTD based Technique*

The indirect lightning, which strikes near a distribution system, radiates an electromagnetic field which causes lightning induced overvoltages on the system. An accurate evaluation of the induced voltages is important to protect distribution systems and power system devices [11].

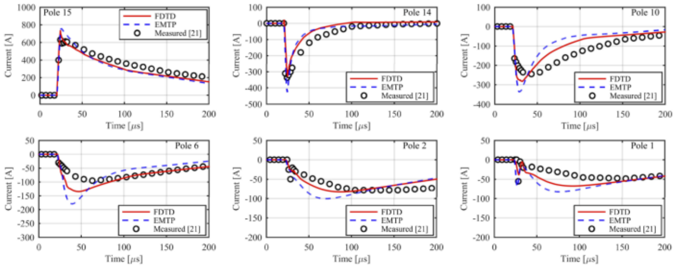
The FDTD method has a key advantage of that it can directly solve Maxwell’s equations. Therefore, it has been adopted into the research on effect of non-vertical lightning on the lightning induced overvoltages in distribution systems and lightning current behavior in a lossy earth [11], [31]-[35].

1) *FDTD analysis of nearby lightning surges flowing into a distribution line via groundings*

A test circuit of transient current measurements due to rocket-triggered lightning on a 15-pole distribution line is illustrated in Fig. 17 (a) [31]. The phase and neutral wires on the line are in a vertical arrangement. Fig. 17 (b) shows comparison of measured ground lead currents I_g and computed results by FDTD and EMTP [31]. Both the polarities and amplitudes of the currents by FDTD agree reasonably well with measured results. More details are presented in [31].



(a) Layout of a field test circuit



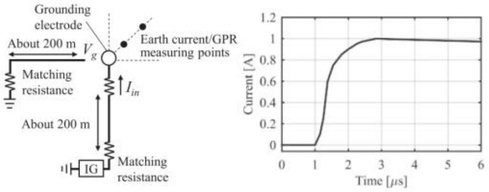
(b) Field measurement and simulation results

Fig. 17 Transient current measurement and simulation due to a lightning strike to ground nearby a distribution line [31].

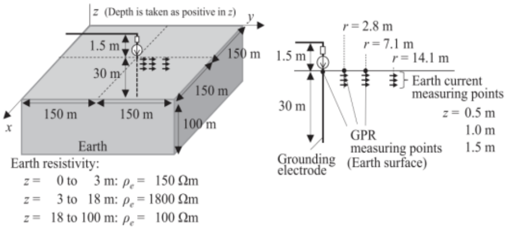
2) Earth current and GPR distributions due to lightning and effect of a distribution line

Reference [32] investigates the distribution of earth current density and grounding potential rise (GPR) due to lightning to the earth surface and to a vertical conductor with a grounding electrode based on measured results and FDTD computations.

A typical result of study is illustrated in Fig. 18 and Fig. 19. FDTD computed results agree reasonably well with the measured GPR results.



(a) Test circuit and I_{in} current



(b) FDTD model circuit

Fig. 18 Field test and FDTD model circuits of earth current and GPR measurements for a 30 m length grounding electrode [32].

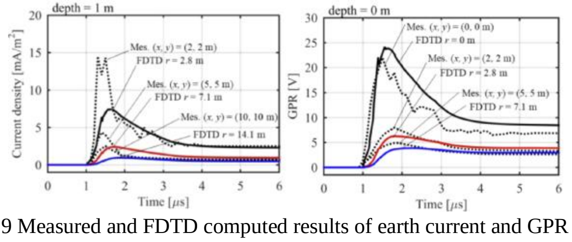


Fig. 19 Measured and FDTD computed results of earth current and GPR [32].

For the current density, larger initial peaks are observed in the measured results while wave tails show good agreement. Although the initial transient phenomenon needs further study, it is confirmed with the measured results that the FDTD can be used to calculate the earth currents and GPRs due to lightning.

3) 3-D FDTD analysis of lightning-induced voltages in distribution lines due to inclined lightning

The influences of inclined lightning on induced voltages in distribution lines by FDTD with single-phase and multiphase lines with a shield wire, poles, groundings, and arresters are investigated in [33]. The FDTD models in the study are validated in comparison with calculated results from analytical formula and numerical calculations.

Fig. 20 illustrates an FDTD model circuit for a multiphase distribution line with utility poles, a shield wire with groundings, and arresters. The details of study are provided by [33]. Fig. 21 shows the influences of lightning-inclined angle θ on the induced voltages at x = 0 m in distribution lines computed by the FDTD. It is clear that the induced voltages are significantly influenced by inclined lightning, especially by the inclination toward the line (angle θ).

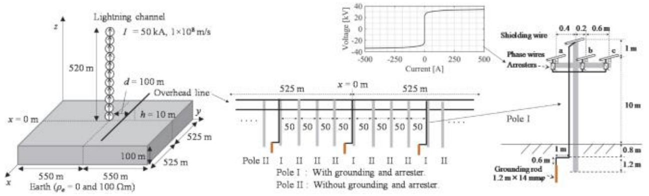
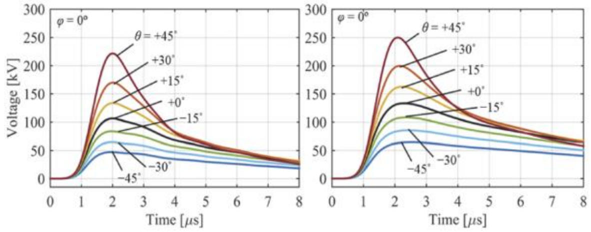
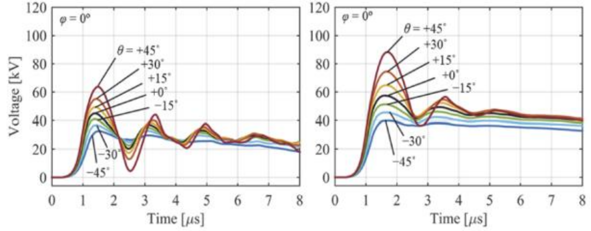


Fig. 20 FDTD model circuit of a multiphase distribution line [33].



(a) Multiphase line with poles and a shield wire with groundings



(b) Multiphase line with poles, a shield wire with groundings, and arresters

Fig. 21 Lightning induced voltages at x = 0 m on Phase B wire of distribution lines due to inclined lightning [33].

V. CONCLUSIONS

This paper presents a summary on contributions performed by Prof. Akihiro Ametani during his stay at Polytechnique Montréal. The contributions of Prof. Ametani remained very important until the end of his life. They can be summarized as follows:

- Theoretical innovation and implementation. It analyzes high frequency transients on overhead conductors. It also proposes new methods on evaluation of parameters on overhead line and underground cable. It supports the development of a new line and cable data calculation tool for the accurate computation of transients.

- Field measurements. The measurements of three real cable systems have been used to improve knowledge on the implemented systems and validate cable modeling for transient studies. The modeling methods validated by practical field measurements contribute to elevate confidence into EMT-type models.
- Numerical electromagnetic analysis. Effectiveness of extended transmission line approach and impact of lightning induced overvoltage in distribution systems are further studied by MoM and FDTD based techniques.

This paper is dedicated to the memory of Prof. Ametani, a great scientist, colleague, mentor and friend. His scholarly example and professional demeanor will not be forgotten.

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