An Electromagnetic Model for the Calculation of Tower Surge Impedance Based on Thin Wire Approximation

Bamdad Salarieh, H. M. Jeewantha De Silva, Aniruddha M. Gole, Fellow, IEEE, Akihiro Ametani, Life Fellow, IEEE, and Behzad Kordi, Senior Member, IEEE

Abstract—When a lightning strikes the top of a transmission line tower or shield wires, electromagnetic waves propagate through the tower back and forth, increasing the voltage across insulator strings. This can eventually lead to a back-flashover (BF), which may cause damage to equipment or costly power outages. To calculate the over-voltages and predict the probability of a BF, an accurate model of the tower and its grounding system is needed in electromagnetic transient (EMT) type simulators. There are a number of theoretical models for the equivalent circuit of a transmission tower. However, they either are not accurate enough or they are derived for a certain type of transmission tower, which limits their applicability. Numerical electromagnetic analyses have less simplifications compared to the theoretical solutions and are by far less expensive than field measurements. They also have the flexibility to analyse any type of tower. In this paper, the direct method for the measurement of tower impedance is implemented by NEC4 and applied to a 400-kV double circuit tower with all its details. The process of obtaining the wire network of the tower used in this paper is completely automated and it can be applied to any other type of transmission tower. The results of the numerical simulations are compared to those obtained with existing tower models. The developed model in this paper is capable of considering all the details of the tower and including the finite resistance of the ground and grounding electrodes.

Index Terms—Electromagnetic analysis, power system transients, numerical analysis, surge protection.

I. INTRODUCTION AND BACKGROUND

The calculation of overvoltages in power transmission lines struck by lightning has been the subject of much research in the past decades. The accurate representation of the transmission line tower and its grounding system is an essential part of the transient behavior of the power system. The advances made in the protection mechanisms require a greater precision in the calculations concerning the transmission line tower.

The approaches for modeling transmission line towers can be divided into three categories: (i) theoretical, (ii) numerical, and (iii) experimental that are performed/implemented either in the time [1]–[14] or frequency domains [15]–[17]. The numerical analyses are based on a) the Method of Moments (MOM) [17]–[19], b) Finite Element Method (FEM) [20], [21], c) Hybrid Electromagnetic Model (HEM) [22], or d) Finite Different Time Domain (FDTD) method. [23]–[28]. Experimental measurements have been performed on full scale towers [28]–[32] or scaled towers [4], [11], [29], [33], [34]. Regardless of the approach, the aim of such analysis is to either find an equivalent impedance or derive an equivalent electric circuit for the transmission line tower with the same response as the measured waveforms. In the theoretical approaches, it is not possible to consider all the tower details, such as its cross arms or bracings. Furthermore, the tower body is approximated by simple geometries such as a cylinder (e.g. [3]) or cone (e.g. [4]). There are only a few experimental studies on a limited number and types of in-service towers as such measurements require an outage and are quite costly. Due to the restrictions of the theoretical and experimental approaches, developing an automated process for the numerical analysis of transmission towers is receiving more attention in recent years.

In this paper, following a thorough overview of the existing models for the transmission line towers and their underlying assumptions, a numerical method based on thin wire approximation of the tower is presented. The Method of Moments (MOM) through Numerical Electromagnetic Code (NEC4) is used to determine the surge impedance of a double circuit transmission line tower either above a perfect electric conductor (PEC) ground or with grounding electrodes buried in lossy ground. The developed model is verified by simulating cylinders of different heights and comparing the results with the measurements available in the literature. Counterpoise grounding electrodes of different lengths (from 5 to 20 m) are considered in soil with resistivity of 100 and 1000 Ωm.

II. DEFINITION OF TOWER SURGE IMPEDANCE

There are three definitions for the time-domain surge impedance of a tower in the literature [35]. The transient surge impedance is a time-domain function and is defined as the ratio of the instantaneous values of the voltage at top of the tower $v(t)$ to the injected current to the tower $i(t)$ [9],

$$ z(t) = \frac{v(t)}{i(t)}. \quad (1) $$
This definition only works for purely resistive circuits, where the voltage and current have the same waveshapes. The other definition of the surge impedance is by considering a step or ramp current injected into the tower and is given by [15]

\[
z(t) = \frac{v(t)}{\max|i(t)|} .
\]

(2)

The commonly-used definition is the ratio of the voltage peak to the current at the time of voltage peak [6] given by

\[
Z = \frac{\max|v(t)|}{T}
\]

(3)

where \(I\) is the value of \(i(t)\) when the voltage \(v(t)\) is maximum. This definition of the surge impedance is not a function of time.

As will be shown in Section V-A, the above time-domain definitions of the surge impedance are dependent on the waveshape of the injected current [35]. In order to mitigate this issue and to define a more general impedance for the tower, the frequency-domain surge impedance given by

\[
Z(f) = \frac{V(f)}{I(f)}
\]

(4)

is used in this paper, where \(I(f)\) is the injected current at the tower top and \(V(f)\) is the voltage at the top of the tower. This definition depends only on the geometry and electromagnetic properties of the tower.

III. An Overview of Tower Models

The large number of existing models for transmission line towers [1]–[10], [16], [26], [27], [29], [30], [36]–[43] can be classified in three categories based on the underlying assumptions and the components used to represent the tower as follows.

1) Vertical Lossless Frequency-Independent Models: These types of models approximate the tower body, i.e., its main legs and cage, with a simple geometric shape such as a cylinder [3]–[9], [38], [41] or a cone [4], [6]. The characteristic impedance of the whole tower as a function of the height above ground is derived using basic electromagnetic field analysis. In some, the current that is injected to the tower is assumed to be of a specific shape, such as a ramp [6], [41], a double exponential [6], [37], or a rectangular wave shape [7], [9], that restricts the applicability of such tower models to other waveshapes. Furthermore, the effect of tower cross arms and bracings is neglected, and the criteria for the selection of the radius of the equivalent structure is not well established. Figure 1A shows a typical double circuit tower, which is considered in this paper, and Fig. 1B shows its representation by such models. Table I shows the surge impedance of the double-circuit tower calculated based on these models.

2) Multisection Lossless Transmission Line Models: In these models, similar to the previous, only the main body of the tower is considered, but it is divided into a number of lossless transmission lines, usually four, and the characteristic impedance of each part is derived by analysing the tower elements as a multiconductor system [1]–[3], [16]. Table II shows the value of the surge impedance in each section for a 4-story tower model as shown in Fig. 1C. In the model of Hara & Yamamoto [3], the tower cross arms are also modeled by horizontal lossless transmission lines (\(Z_{L_1}\)), and the bracings are modeled by a surge impedance (\(Z_{L_1} = 9Z_{T_1}\)) in parallel to the tower main body in each section, as shown in Fig. 1D.

3) Multistory Tower Models: As shown in Figs. 1E and 1F, these tower models divide the tower into four segments at the upper, middle, and lower phase arm positions. Each section consists of a lossless transmission line \(Z_T\) in series with a parallel \(RL\) circuit [26], [27], [29], [30], [42]–[44]. The resistance represents the attenuation of traveling waves in the tower, and the inductance makes the resistance ineffective as time passes by and also adjusts the propagation velocity along the tower [30]. These models are derived based on the results of field measurements on actual towers and the values of the tower surge impedance and attenuation coefficients have to be determined by a trial and error process such that the response of the circuit representing the tower would be the same as the measured ones. There are limitation in extending the results of such models to other types of transmission towers [30]. Table III shows the values of tower parameters calculated based on these models, and the equivalent circuit of the tower is shown in Fig. 1E. In the model proposed by Ishii and Baba [43], two parallel \(RL\)

### Table I

<table>
<thead>
<tr>
<th>No</th>
<th>Model</th>
<th>Expression</th>
<th>(Z_T (\Omega))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wagner &amp; Hilemen [9]</td>
<td>60 ln(√2 (\frac{h}{r_0}))</td>
<td>205</td>
</tr>
<tr>
<td>2</td>
<td>Jordan [6]</td>
<td>60 ln((\frac{h}{r_1})) - 60</td>
<td>129</td>
</tr>
<tr>
<td>3</td>
<td>Sargent &amp; Darveniza [6]</td>
<td>60 ln((\sqrt{\frac{h}{3}})) - 60</td>
<td>195</td>
</tr>
<tr>
<td>4</td>
<td>Sargent &amp; Darveniza [6]</td>
<td>60 ln((\sqrt{\frac{h}{2}}))</td>
<td>150</td>
</tr>
<tr>
<td>5</td>
<td>Menemenlis &amp; Chun [37]</td>
<td>50 + 35(\sqrt{h})</td>
<td>285</td>
</tr>
<tr>
<td>6</td>
<td>Chisholm et al. [4]</td>
<td>60 ln((\cot(\frac{\tan^{-1}(\frac{r_{0}}{r})}{2})))</td>
<td>184</td>
</tr>
<tr>
<td>7</td>
<td>Chisholm et al. [4]</td>
<td>60 ln((\cot(\frac{\tan^{-1}(\frac{r_{0}}{r})}{2}))) - 60</td>
<td>124</td>
</tr>
<tr>
<td>8</td>
<td>Chisholm et al. [3]</td>
<td>60 ln((\cot(\frac{\tan^{-1}(T)}{2})))</td>
<td>150</td>
</tr>
<tr>
<td>9</td>
<td>Flash version 1.7 [38]</td>
<td>60 ln((\frac{h}{r_0})) - 120</td>
<td>150</td>
</tr>
<tr>
<td>10</td>
<td>Hara &amp; Yamamoto [3]</td>
<td>60 ln((\frac{h}{r_0})) - 120</td>
<td>167</td>
</tr>
<tr>
<td>11</td>
<td>De conti et al. [8]</td>
<td>60 ln((\frac{h}{r_0})) - 60</td>
<td>166</td>
</tr>
<tr>
<td>12</td>
<td>IEEE WG [41]</td>
<td>60 ln((\frac{h}{r_0}))</td>
<td>142</td>
</tr>
<tr>
<td>13</td>
<td>Takahashi [7]</td>
<td>60 ln((\sqrt{\frac{h}{2}})) + 1.54</td>
<td>112</td>
</tr>
</tbody>
</table>

1 The radius of the tower at its base, waist and top are \(r_0\), \(r_1\), \(r_2\), respectively.
2 The height of the tower is \(h\), height from base to waist is \(h_1\) and height from waist to top is \(h_2\).
3 \(T = (r_2h_2 + r_1h + r_0h_1)/h^2\).
elements are considered in the lower tower section as shown in Fig. 1F.

IV. Verification of the Numerical Analysis

Measurement of the tower surge impedance is performed in two ways: one is the direct method [11], [31], where a current pulse is injected into the tower top and the voltage between the tower top and a reference voltage measuring wire is measured using a voltage divider. The other method is the reflection method [45], where a steep-front traveling wave is injected into the tower top using a wire, and the reflected wave is observed to estimate the transient impedance of the tower. In this paper, the former method of measurement is implemented using numerical simulations, since the reflection method is only valid when evaluating the reflection of waves from adjacent towers [46]. The simulations are performed using Numerical Electromagnetic Code (NEC-4), which is based on the thin wire approximation and the numerical solution of integral equations by means of the Method of Moments (MOM) [47]. Measurements of the surge characteristics of cylinders with different heights and radii performed by Hara et al. [44] are employed to validate the accuracy of the numerical simulations. In the measurements of [44], the electrodes are placed on a 12 × 10 m² iron plate as the ground as shown in Fig. 2. The current is applied to the top of the vertical conductor by a current lead extended horizontally 9 m away. The voltage is measured using a voltage probe in the gap between the top of the cylindrical conductor and a voltage reference wire, which is horizontally extended to the remote ground and it is perpendicular to the current lead wire to minimize the coupling effects. Both the current and voltage wires are attached vertically to the ground at their ends, using a matching resistance ($R_e$) to avoid reflections.

The measurement performed on a 3-m high cylinder with a radius of 2.5 mm is considered for the numerical analysis in NEC4. A 10 kΩ resistance is inserted between the top of the electrode and end of the voltage reference wire. The voltage is evaluated by calculating the current flowing through this resistor. It shown that the value of the voltage-measuring probe has no significant impact on the measurement if its internal capacitance is less that a certain limit [48]. Finally, the inverse Fourier transform is used to obtain the time domain voltage and current.

The voltage waveform shown in Fig. 3, adopted from [44], is used as the input to the system. Figure 3 shows the
TABLE III  
Surge impedance of the double circuit tower calculated by multistory tower models.  

<table>
<thead>
<tr>
<th>No</th>
<th>Model</th>
<th>$Z_{T1}(\Omega)$</th>
<th>$Z_{T2}(\Omega)$</th>
<th>$Z_{T3}(\Omega)$</th>
<th>$Z_{T4}(\Omega)$</th>
<th>$R_1(\Omega)$</th>
<th>$R_2(\Omega)$</th>
<th>$R_3(\Omega)$</th>
<th>$R_4(\Omega)$</th>
<th>$L_1(\mu H)$</th>
<th>$L_2(\mu H)$</th>
<th>$L_3(\mu H)$</th>
<th>$L_4(\mu H)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>Yamada [29]</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>9.30</td>
<td>16.45</td>
<td>17.06</td>
<td>42.80</td>
<td>2.79</td>
<td>4.94</td>
<td>5.13</td>
<td>12.86</td>
</tr>
<tr>
<td>20</td>
<td>Motoyama [42]</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>3.83</td>
<td>11.70</td>
<td>9.32</td>
<td>26.80</td>
<td>2.31</td>
<td>4.61</td>
<td>3.69</td>
<td>10.69</td>
</tr>
<tr>
<td>21</td>
<td>Baba [43]</td>
<td>200</td>
<td>200</td>
<td>180</td>
<td>150</td>
<td>20</td>
<td>30</td>
<td>25</td>
<td>25</td>
<td>6</td>
<td>9</td>
<td>15</td>
<td>1.5</td>
</tr>
<tr>
<td>22</td>
<td>Hashimoto [27]</td>
<td>195</td>
<td>182</td>
<td>149</td>
<td>121</td>
<td>13.30</td>
<td>32.50</td>
<td>28.10</td>
<td>76.10</td>
<td>7.42</td>
<td>18.10</td>
<td>15.70</td>
<td>52.7</td>
</tr>
</tbody>
</table>

As a result, the effect of grounding system appears after the peak of the voltage waveform. The voltage at the top of the cylinder relative to the voltage reference wire is shown in Fig. 4. The rise time of the voltage waveform is almost equal to the rise time of the injected current and there is a reflection from the ground at $t_0 = 100$ ns. Calculating the surge impedance of the tower for the considered excitations using (3), $Z$ varies from 324.6 to 293$\Omega$, which is equal to a variation of 9.7%, when the rise time is increased from 10 to 80 ns. Considering a double exponential excitation waveform, which is commonly used in lightning studies, the surge impedance defined by (3) decreases from 316.8 $\Omega$ for a rise time of $T_1 = 10 \mu s$ to 232.5 $\Omega$ for a double exponential waveform with a rise time of $T_1 = 200 \mu s$. 

![Fig. 3. Voltage at the top of the cylinder with reference to remote ground (right axis) and measured and simulated current (left axis) injected at the top of a 3-m cylinder on a PEC ground.](image)

![Fig. 4. Simulated voltage at the top of a 15-m vertical cylinder in response to pulse currents of 1 A in magnitude and rise time of $t_r$ injected at the tower top.](image)

measured and simulated currents injected at the top of the cylinder that shows the accuracy of simulation results, in terms of both the waveshape and magnitude. The measured current initially rises for 5 ns and remains almost constant till $t = 20$ ns that is when the reflected wave from the ground reaches the top of the cylinder.

V. Results and Discussions

In this section, firstly, the simulation results are presented for vertical cylinders and the double-circuit tower (shown in Fig. 9) on a PEC ground. The dependence of time-domain surge impedance and the effect of tower elements are investigated. Finally, the effect of lossy ground on the simulated results is presented and discussed.

A. Dependence of Time-Domain Surge Impedance on the Excitation Waveshape

In this section, we also employ the measurements of Hara et al. [44] are considered to show the dependence of time-domain impedance definitions on the waveshape of the excitation. In [44], the so-called maximum surge impedance, as given in (3), was used. A step input current with a rise time of 5 ns is applied to the cylinder (see Fig. 2) and the surge impedance is calculated at $t_0 = 2h/c$, where $h$ is the height of the cylinder and $c$ is the speed of light. For the case of a cylinder with a height of 15 m and a radius of 25.4 mm, the measured surge impedance is 320 $\Omega$ [44]. The same cylinder is simulated in NEC4 in the frequency range of 0.1 to 250 MHz. The length of the current and voltage leads are 115 m, so that the reflected waves do not affect the results until 700 ns. Step currents with various rise times from $t_r = 10$ to 80 ns are injected into the top of the cylinder. The values of $t_r$ are less than the round-trip travel time of the wave along the cylinder, which is equal to $t_0 = 100$ ns.
be justified by considering the opposing effects that adding the shield wire cross arms and tower bracings have on the impedance of the tower [17]. In all four cases, the apparent travel speed is lower than 91% of the speed of the light due to the presence of different tower elements that increase the propagation path of the waves.

VI. COMPARISON OF THEORETICAL AND SIMULATION RESULTS

In this section, to assess the accuracy of different tower models on the prediction of tower top voltage, they are compared with the numerical results for the case of the vertical cylinders with heights of 15, 45, and 90 m. They are also compared with the numerical results for the case of the double circuit tower over a lossy ground.

A. Vertical Cylinders

Figures 7a and 7b show the voltage at the top of the cylinder for the case of a vertical cylinder with a height of 15 m on a PEC ground when injected with currents with rise times of \( t_r = 80 \) and \( t_r = 10 \) ns, respectively. This figure presents a comparison of 11 of existing models with that obtained using NEC4. The predicted waveform of the theoretical solutions is closer to that obtained by NEC4 when the rise time of the injected current is 80 ns (see Fig. 7a). Whereas, in the case of a rise time of 10 ns, the calculated waveshapes using the theoretical models are step-like and are different from the simulated voltage in NEC4, which shows a slower rise-time and decay. This is due to the fact that the early-time electromagnetic fields around the cylinder is different from TEM but the theoretical models assume the electromagnetic fields are always TEM.

B. Double Circuit Tower

Figure 8a shows the voltage at the top of the double circuit tower obtained using NEC and theoretical approaches 4 and 7 from Table I and 14 and 17 from Table II, for which we used the method of characteristics of partial differential equations theory [49]. A rise time of \( t_r = 150 \) ns is considered such that the rise time is less than the travel time. In the theoretical approaches, the wave propagation speed is assumed to be the speed of light, however, in the numerical result shown in Fig. 8a, the apparent wave speed is equal to 87% of the speed of light. This is in agreement with measurements which suggest 80% [6], 71%, 76%, 81% and 89% of the speed of the light.
Fig. 7. Comparison of the voltage at the top of a 15-m cylinder obtained by numerical analysis and the models of Tables I and II. The excitation current is a ramp with a rise time of (a) $t_r = 80$ ns and (b) $t_r = 10$ ns.

[31]. This justifies why the zero crossing of the NEC result is at a later time in comparison with the theoretical results. The multiconductor model of Ametani [16] and the model of Hara & Yamamoto [3] show the closest values of the surge impedance (relative difference of 5.3% and 6.8%).

Now, let’s consider a model of the double-circuit tower with all its details with the same current injected to the top of the tower. The multistory models of Table III are compared with the numerical analysis in Fig. 8b. Regarding the voltage peak, the closest predicted values are by the models of Yamada [29] (error of 2.8%) and Motoyama (error of 8.4%) [42]. Considering the waveshape of the voltage, the models of Yamada and Motoyama are closer than the others ones to the one predicted by NEC. However, the model of Hashimoto [27] shows a closer decaying part than the other models. As stated in [27], this is due to the modification in the derivation of this model in order to reproduce the gradual decay of the measured voltages. All of the multistory models of Table III require “tuning” based on measured waveforms from a specific tower structure, whereas our approach based on numerical simulation solely requires the geometrical information of the tower. For example, the model of Ishii which has a large overestimation of the voltage, was derived for Japanese 500 kV [30] and UHV towers [29] that are taller (62.8 and 140.5 m) than the typical double circuit towers like the one considered in this paper (45.1 m). The results shown in this section, demonstrate the multistory models of Table III have limited applicability.

VII. EFFECT OF GROUNDING SYSTEM

In the previous sections and most previous studies (e.g. [3], [4], [10]), the ground was assumed to be a Perfect Electric Conductor (PEC). However, in reality the conductivity of ground is finite. In this section, we consider a lossy ground where counterpoise grounding electrodes, 1, 2, 5, 10 and 20 m in length, are considered as the grounding system of the tower (see Fig. 9).

The burial depth of the electrode is assumed to be 1 m with an optimized opening angle of the electrodes of 45° [21]. Two soil resistivities of 100 and 1000 $\Omega\cdot$m are considered. Fig. 10a shows the simulated and theoretical voltage at the top of the tower when counterpoise grounding electrodes of 20 m in length buried in soil with a resistivity of 100 $\Omega\cdot$m are considered. To obtain the response of theoretical tower models, first an electromagnetic simulation is performed on counterpoise grounding electrodes using the model presented...
in [50], to obtain their low frequency resistance. The obtained values agree well with the analytical formula provided in IEEE Std. 1243 [38]. This resistance is added to the tower models and the simulation is performed in PSCAD/EMTDC. The injected current is a 2/50 μs double exponential with a peak of 1 A, and a shunt internal resistance of 5 kΩ [51] is considered to have the same condition as the numerical simulation. The most noticeable difference between an ideal and lossy ground is the difference in the peak of the voltages predicted by theories that is less in the case of a lossy ground but still considerable. Considering the NEC results, the models of Baba [18] and Yamada [29] produce the closest results considering both the peak of the voltage and its waveshape. The difference in the peak of the voltage is 2.5% and 5.6%, respectively. Assuming a soil resistivity of 1000 Ωm, the same tower models as above generate the closest results to those generated by NEC (see Fig. 10b). However, the difference (9.41% for Baba [18] and 20.45% for Yamada [29]) is higher as the resistivity of the soil is increased. In general, the theoretical tower models are a fast way to have an estimation of the developed overvoltages on a transmission tower, but they are not accurate for all tower models and the value of circuit elements need to be tuned for every topology of the tower using field measurements. Furthermore, the effect of excitation waveshape on the accuracy of predicted overvoltages is another challenge for the theoretical tower models.

VIII. Conclusions

In this paper, a detailed wire-model of a typical 400 kV double-circuit tower with a height of 45.1 m was generated using an automated process that employs the CAD drawing of the tower. The wire model was then used in NEC4 to calculate the transient tower top-voltage considering the finite conductivity of the ground and grounding electrodes. It was shown that the definition of tower surge impedance based on time domain voltage and current has a main disadvantage of being dependent on the excitation waveshape and rise time. Following a review of existing transmission tower models, they were compared with the results of NEC4 for the case of a simple cylinder and the 400 kV double-circuit tower. Regarding the peak of the tower top voltage, the theoretical models could provide close predictions to that of NEC4. Considering the voltage waveshape, theoretical models were not able to generate results close to those determined by NEC4 in the case of fast-front currents, because the initial electromagnetic field around the cylinder is not TEM. In the case of the double-circuit tower on a PEC ground, the models of Yamada [29] (difference of −2.8%) and Motoyama [42] (difference of −8.4%) had the closest similarity to NEC4 results with regards to the calculated voltage peak.

The proposed model based on NEC is capable of considering the effect of the finite conductivity of the ground. In order to compare this model for the case of a lossy ground, a grounding resistance was added to the theoretical models. The models of Baba [18] (difference of +2.5%) and Yamada [29] (difference of −5.6%) provide closer peak values to that of NEC4, although the error can not be considered as negligible (when ρ = 1000 Ωm, the error is −9.41 and −20.45%, respectively). The previous models of transmission towers were derived based on either electromagnetic field analysis on a simplified model of the tower (approximated by a cone or cylinder), or by a trial-and-error process to find the resistance and inductance values of the circuit such that they produce similar waveforms as the measurements. The multistory tower models may be able to provide accurate results if the circuit values are tuned, but the process of such tuning is not well established. This paper demonstrated that such models cannot provide accurate results in the case of a typical double-circuit tower that they have not been tuned for. The proposed process in this paper has the advantage of needing only the geometry of the tower and it can be further applied to any other type of transmission towers.

References

Bamdad Salarieh received the B.Sc. degree in electrical engineering from Sharif University of Technology, Tehran, Iran, and M.Sc. degree in electrical engineering from University of Manitoba, Winnipeg, MB, Canada, in 2017, and 2020, respectively. He is currently a research engineer at Manitoba Hydro International, Winnipeg, MB, Canada. Bamdad was the recipient of the Young Scientist award at IPST 2019 conference. His research interests include Electromagnetic transients of power systems, lightning electromagnetics, and renewable energy.

H. M. Jeewantha De Silva received B.Sc. (Eng) degree at University of Moratuwa, Sri Lanka in 2001 and then Ph.D from University of Manitoba, Canada in 2009 on accurate simulation of transmission lines and cables. Dr. De Silva is a Power System Simulation and Research Engineer at the Manitoba Hydro International, Canada since 2009. He is involved with improving overhead transmission lines and cable models in PSCAD/EMTDC commercial software and also Electromagnetic Transient Program (EMT) algorithms and simulation tools. He is also involved in power system simulation studies and supporting PSCAD clients.

Behzad Kordi (M’05, SM’12) received the B.Sc. (with distinction), M.Sc., and Ph.D. degrees all in electrical engineering from Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran, in 1992, 1995, and 2000, respectively. During 1998 and 1999, he was with the Lightning Studies Group at the University of Toronto, Canada. In 2002, he joined the Electrical and Computer Engineering Department, University of Manitoba, Canada where he is currently a full professor and the director of McMath High Voltage Laboratory. His research interests include high voltage engineering, electromagnetic compatibility, simulation models of power transformers and transmission lines, and condition monitoring of high voltage apparatus. Dr. Kordi was the chair of URSI Canada Commission E in 2012-13. He is a member of a number of Cigré working groups pertinent to transient modeling of power system apparatus. He is also an associate editor of IEEE Transactions on Dielectrics and Electrical Insulation and IET High Voltage. Dr. Kordi is a registered professional engineer in the province of Manitoba and was the recipient of 2012 IEEE EMC Richard B. Schulz best transactions paper award.

Aniruddha M. Gole (M’82, SM’04, F’10) is a Distinguished Professor and NSERC Industrial Chair in Power Systems Simulation at the Department of Electrical and Computer Engineering, University of Manitoba. He has over 30 years of experience in the development of modelling tools for power networks incorporating power-electronic equipment such as HVDC and FACTS converters. He is one of the original developers of the widely used PSCAD/EMTDC simulation program. Dr. Gole has also made important contributions to the development of the real-time digital simulator RTDS from RTDS Technologies of Winnipeg, Canada. Dr. Gole is a Fellow of the Canadian Academy of Engineering and an IEEE Fellow. For his contributions to the modelling of Flexible AC Transmission System (FACTS) devices, he received the IEEE Nari Hingorani FACTS Award in 2007. Dr. Gole is a member of the Long Range Planning Committee of the IEEE Power and Energy Society.

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Akihiro Ametani (M’71, SM’83, F’92, LF’10) received the Ph.D. degree from UMIST, Manchester, U.K., in 1973, and the D.Sc. from the University of Manchester, Manchester, U.K., in 2010. He was with Bonneville Power Administration, Portland, OR, USA, to develop electromagnetic transients program from 1976 to 1981. He was a professor with Doshisha University, Kyoto, Japan, until March 2014, and with Polytechnique Montréal, Montreal, Canada, from 2014 to 2018. Currently, he is a professor with the University of Manitoba, Winnipeg, Canada. He was the Chairman of the Doshisha Council from 2011 to 2014. He served as a Vice-President of the IEE Japan in 2003 and 2004.