Abstract—In this paper, by creating a 3-D model of power-line equipment and lightning leader progression models, an alternate procedure for calculating the shielding failure rate (SFR) of transmission lines is presented. The stepping nature of lightning downward leader is modeled according to field observations with the use of discrete line charges approaching the earth. A simplified self-consistent model for an upward connecting leader is also adopted to find the position of lightning incidence to the transmission line. The required electric field in an environment is computed by using the charge simulation method. A comparison has been made between the SFR calculated by proposed method and the values calculated by conventional electrogeometrical model. In addition, different previously proposed incidence criteria are implemented and compared. Some comparisons are also made between the calculated SFR and available field data for selected overhead lines.

Index Terms—Charge simulation method, downward leader, self-consistent model, shielding failure rate, upward leader.

I. INTRODUCTION

T he electrogeometrical model (EGM), which was initially proposed by Young [1], has long been used as a main engineering method for transmission-line lightning performance investigation and design. In essence, the EGM is sensitive to the way that lightning stroke characteristics are represented (i.e., the striking distance equation). Different striking distance equations have been proposed so far [1]–[8]. The modified-electrogeometrical model (MEGM) is also proposed by Eriksson [7] which changed the technique for shielding failure-rate (SFR) calculation of overhead transmission lines. Nevertheless, there are different approaches that some investigators have used for lightning performance analysis of transmission lines and SFR calculation [9]–[11]. Among them, the leader progression family absorbs more interests [9], [11], [12]. The leader progression model (LPM) tracks the route of the downward lightning leader and an upward connecting leader to find the stroke attachment point to the overhead line and, hence, models the breakdown phenomena more accurately. However, the effect of the pockets of space charges that exist between the base of the cloud and surface of the ground are ignored by LPM. This simplification causes unquantified errors in the calculations, because those pockets of charges actually affect the development and steps of the downward leader. Accepting these errors, an alternative approach based on LPM is introduced in this paper to calculate the SFR of transmission lines in a 3-D environment using a charge simulation method which takes the upward lightning leader and stepping nature of the downward lightning leader [12] into account. Previously, a simple leader model was used to implement LPM in three dimensions and critical-length criterion [13] and Rizk’s formula [14] was used to find the incidence point of a descending lightning leader [12]. Actually, the descending lightning leader and its charge, the complex earthed structure of the transmission line, and space charge of the upward lightning leader enhance the field in the environment and consequently affect the result of SFR calculation [12]. Recently, a self-consistent model of positive upward connecting leader has been introduced which considers the space charge effects of the upward leader-streamer system [15]–[17]. In this paper, our main goal is to modify the lightning leader’s way of modeling to implement the simplified self-consistent model for the upward connecting leader and stepping nature for the downward leader to analyze the lightning performance of overhead transmission lines. The charge simulation method is used to evaluate voltage and its gradient in computing space at each calculation step [18], [19].

A comparison has been made between different incidence criteria and a self-consistent model of an upward connecting leader on SFR calculation. The prediction of EGM with different striking criteria is also compared with the full dynamic procedure of the proposed method. Moreover, the simulation results are compared with available shielding performance statistics for some overhead lines.

The rest of this paper is organized as follows. In Section II, the configuration setup for modeling the clouds, towers, and wires is described. Stepping downward and self-consistent upward lightning leader models are presented in Section III. Section IV introduces the leader propagation procedure and SFR calculation results. Finally, Section V concludes this paper.

II. CONFIGURATION SETUP FOR SFR CALCULATION

The SFR calculating procedure for a specified configuration of towers, conductors, and space charge of upward and downward leaders requires electric-field calculation in the environment of study. When using the charge simulation method, the ring, point, and line charges are placed in arbitrary places to enforce specific values for boundary conditions according to the problem definition. In this section, the charges and contour
points to be placed for modeling the clouds, towers, and wires are discussed.

A. Cloud Charges

The clouds are modeled as a simplified unipolar negative charge on the height of 2000 m and with an extension of 5000 m. According to the field tests, the storm field is said to produce the electrical field on ground level in the range of 1–20 kV/m [20]. Thus, in each calculation step, the cloud charges are calculated so that the field near the ground becomes 10 kV/m. Fig. 1(a) depicts the model of cloud charges.

B. Charges for the Towers

Based on the approach of [12], ring charges are used to satisfy the zero voltage boundary condition at the tower structures. In this paper, the base, the cross arms, and upper ground wire legs are considered in the model with the help of ring charges and contour points which are shown in Fig. 1(b). By assuming the contour points around the tower in the middle of consecutive ring locations, the zero voltage boundary condition in three dimensions around the tower tries to be achieved.

C. Charge for the Wires

For the wire boundary conditions, zero voltage for shield wires and peak phase to ground positive voltage for the middle phase are assumed. Subsequently, the voltages of other two phases are known. Short horizontal and vertical-line charges are used to model the wires and their sag with well-known hyperbolic functions [12]

\[
\begin{align*}
    z &= h \cdot \cosh \left( b \cdot \frac{D}{2} - x \right) \\
    b &= \frac{2}{D} \ln \left( \frac{H - \sqrt{H^2 - h^2}}{h} \right)
\end{align*}
\]

where $h$ is the height of the wire at midspan, $H$ is the height of the wire at connection point to towers, and $D$ is the span length as shown in Fig. 1(c). It is important to note here that with the aforementioned models, the sloped shape of wires is replaced by the horizontal and vertical-line charges. In the EGM family methods of SFR calculation, this problem is cured by modeling the towers and slopes of segments of the wires [21]. In our leader progression approach, the number of vertical and horizontal segmental lines affects the results. It is then important to have segments that are large enough to ensure low errors that have occurred with this type of modeling. We will discuss more about this issue in Section IV.

III. MODEL OF DOWNWARD AND UPWARD LIGHTNING LEADERS

These days, fast computers can be used to simulate the propagation of lightning and the striking process step by step. The field enhancement with space charges of downward and upward lightning leaders and the way they are implemented in computer programs, affects the return stroke peak current range of strokes passing the shields and, subsequently, they affect the results of SFR calculation. Hence, it is crucial to adopt more precise models for downward and upward lightning leaders.

A. Downward Leader

The negative downward lightning leader is replaced by line charges on each downward leader jump. Fig. 2 shows the line charges for a descending downward leader. Simulation starts with the vertical straight section of the leader discharge developed up to a level which is high enough to nullify the influences of the earthed objects. Since an object standing alone on the earth causes a distortion of the field only up to the level of twice its height, the starting point of the simulation must be above this level [22].

Based on the available photographs of the negative downward lightning leader, it approaches the earth with a series of rapid and discontinuous steps [23]. The length of steps ranges from 10 to 100 m. The average length of steps in higher altitudes is about 50 m and it reduces to 10 m near the ground [23], [24]. In this paper, the propagation is represented by steps with a length of $1/k$ of distance of the tip of the downward leader.
from ground, where \( k \) is assumed to be the initial altitude of the downward leader divided by 100 m. Therefore, the step length becomes always lower than 100 m in accordance with field observations. Similarly, if the downward leader approaches near the earth until the aforementioned equation yields a step length lower than 10 m, the step length is set to 10 m. By assuming the direction of the downward leader so that the potential gradient is maximum, a hemisphere with a radius of the step length around the tip of the downward leader is drawn. Since the potential is always negative (assuming negative downward leaders), the next jump point of the leader is a point on the hemisphere where the absolute value of potential is the lowest (i.e., the maximum voltage gradient along the line connecting the leader tip to the target point is ensured) \([12]\) (see Fig. 2). The steps of the downward leader are modeled by horizontal and vertical line charges (similar to II-C). The charge density of the downward leader is computed by the recently proposed equation which is derived based on electrostatic considerations of measured waveforms of the return-stroke current and can be expressed by (3) and [8]

\[
\rho(z) = I_p \left\{ m_0 \left(1 - \frac{z-z_0}{H-z_0}\right) \left(1 - \frac{z_0}{H}\right) \right.
\]

\[
+ \left. \frac{1}{m_1 + m_2 (z-z_0)} \right) \times \left[ 0.3 \left( \frac{10^{-10}}{z_0} + 0.7 \left(1 - \frac{z_0}{H}\right) \right) \right]
\]

(3)

where \( m_0 = 1.476 \times 10^{-5} \), \( m_3 = 4.857 \times 10^{-5} \), \( m_2 = 3.9007 \times 10^{-6} \), \( m_3 = 0.522 \), \( m_4 = 3.73 \times 10^{-4} \), \( z_0 \) is the height of the downward leader tip in meters, \( H \) is the cloud height in meters, \( I_p \) is the return stroke peak current in kiloamperes, \( \rho \) is the downward leader charge density in C/m, and \( z \) is the variable height of the point on the leader where charge density is to be calculated, see Fig. 2. It is worth noting here that according to (3), the charge density has a sharp variation near the downward leader tip. Thus, the length of line charge sections near the tip is set to be shorter.

B. Upward Leader

When the negative downward lightning leader approaches the earth, an increasing electric field (near 3000 kV/m) on earthed structures may lead to local ionization near some sharp points which is said to be the corona inception time. In fact, the point of strike is a point on ground structures where a stable positive upward leader inception can be incepted. Different criteria have been proposed for calculating electric-field intensity to ensure stable upward leader inception \([9], [13], [17], [25]\). Among them, the self-consistent model \([16], [17]\) takes care of space charge development and transition of the corona streamer to the leader-streamer upward connecting system.

In Fig. 3, the leader streamer system and voltage distribution of a sharp point are shown. To implement the self-consistent model, the streamer zone charge is initially calculated in, say, zero steps \([17]\)

\[
I_s^0 = \frac{U_0}{E_a - E_b}
\]

\[
\Delta Q^0 = 0.5 \cdot K_Q \cdot I_s^0 \cdot (E_a - E_b)
\]

(4)

(5)

where \( U_0 \) and \( E_b \) are the voltage and field on the fitted line of background electric field as depicted in Fig. 3. \( E_a \) is the constant streamer zone electric field which is taken to be 450 kV/m for positive upward leaders \([26]\), \( I_s^0 \) is the initial length of the streamer zone, and \( K_Q \) is a geometrical factor that takes into account the effect of all streamers on the total streamer zone charge. The necessary (not enough) condition for stable upward leader inception is that \( \Delta Q^0 \) may be high enough (\( \geq 1 \mu C \)) for the streamer zone to change into a leader-streamer system \([25]\).
If this condition fulfilled, then by taking the initial leader length as being 1 cm, the streamer zone length and streamer zone space charge are calculated in each leader advancement step \((i \geq 1)\):

\[
U_{i_{\text{tip}}}^0 = E_{\text{inf}} \cdot l_i^0 + x_0 \cdot E_{\text{init}} \cdot \ln \left[ \frac{E_{\text{init}}}{E_{\text{init}} - E_{\text{inf}}} \right] - \frac{q_l}{x_0}
\]

\[
l_i^0 = \frac{U_0 + E_a \cdot l_i^0 - U_{i_{\text{tip}}}^0}{E_a - E_b}
\]

\[
\Delta Q^i = K_Q \cdot (l_i^0 - l_i^{-1})
\]

\[
\Delta l_i = \frac{\Delta Q^i}{q_l}
\]

\[
l_i^{i+1} = l_i^0 + \Delta l_i
\]

where \(U_{i_{\text{tip}}}^0\) is the leader potential in step \(i\), \(E_{\text{inf}}\) and \(E_{\text{init}}\) is the initial value and final quasistationary value of the leader gradient, and \(x_0\) is a constant equal to \(v \cdot \beta\) where \(v\) is the ascending leader speed and \(\beta\) is the conductance equation time constant. \(q_l\) is a constant that represents the charge per-unit length necessary to achieve the thermal transition from the diffuse glow to the leader channel [26]. The procedure continues until \(\Delta Q^i\) is positive. If \(\Delta Q^i\) becomes negative, no stable upward leader is incepted. Usually this procedure continues until leader elongates to a predefined \(l_{\text{max}}\).

In Table I, the constants of the upward leader model are presented. Of particular interest is the fact that the predictions of the upward connecting leader model will vary due to parameter changes which can occur just because of the environmental conditions. The model sensitivity to parameters is analyzed in [17]. The sensitivity of SFR, calculated by the proposed method to the parameters of the upward connecting leader model, is to be discussed in an independent paper which deals with the effect of environmental conditions on the calculated SFR by the proposed method.

The following points should be noted to fit the aforementioned self-consistent model into the proposed method of SFR calculations correctly.

1) The background electric field in each calculation step is computed by the charge simulation method. The space charges of downward and upward leaders are known, and the system of linear equations of the charge simulation method is solved to find the unknown ring and line charges on the towers and wires.

2) During the charge simulation computation, the charges of downward and upward lightning leaders are assumed to be known. Those charges are computed by using (3) and (8).

3) Two conditions should be satisfied to ensure stable upward leader inception from any test point: 1) the initial space charge \(\Delta Q^0\) should be high enough to start the transition of corona charges to the leader-streamer system \((\geq 1 \mu C)\) and 2) up to reaching a predefined leader length, \(\Delta Q^i\) always stays positive.

4) According to the literature, simulating the conditions for leader advancement to \(l_{\text{max}} = 2 - 3\) m is enough to find whether the stable positive upward leader is incepted or not [17]. Thus, it will decrease the computing time (which is, in essence, rather high) considerably.

5) All upward leaders are assumed to be directed to the tip of the downward leader in each electric-field computing step.

6) If in a situation, more than one stable leader from different points in towers or wires is initialized, it is assumed that the lightning will strike a point where the upward connecting leader from that point reaches the downward leader tip sooner (i.e., the simulation continues until the upward leaders connect the downward leader tip). The strike point is a point where lower steps are required, according to (10) to reach the downward leader tip.

7) The ground strike will occur if in any step of the downward leader approaching the ground, the downward leader tip distance becomes lower than the striking distance to ground, see Fig. 4. To be on the safe side, the striking distance equation, which yields the lowest striking distance to ground for the simulated range of return stroke peak currents, has to be utilized (i.e., Cooray et al. [8] striking distance equation, see Table III). It is worth mentioning here that it is possible to continue simulation until the downward leader tip reaches the ground to ensure ground strikes; however, the simulation time will increase dramatically. Therefore, testing the ground strike in advance would be quite efficient.

### IV. PROGRESSION MODEL AND SFR CALCULATION

The procedure and steps of performing the analysis are shown in Fig. 4. Using the configuration of one span (two towers, conductors, and a perfectly conducting ground), the space above the span is divided into meshes [12]. The width of area in the Y direction according to Fig. 5, where the simulation should be performed, is selected so that out of this area, no flash to wires and towers occurs. Owing the symmetry which exists in the problem, it is enough to perform the procedure of Fig. 4 for 1/2 of the span length and 1/4 of the span area, see Fig. 5. For each mesh, a range of return stroke currents is scanned to find the min and max return stroke currents \((I_{\text{min}}, I_{\text{max}})\) in which the lightning leaders strike the phase wires. Then, the shielding failure rate on each mesh can be computed

\[
\text{SFR}_{ij} = 0.1 \times \text{GFD} \times \frac{dx}{dy} \times [P(I_{\text{max}}) - P(I_c)]
\]

where \(dx\) (in meters) and \(dy\) (in meters) are the mesh length and width according to Fig. 5, \(D\) (in meters) is the span length. \(\text{SFR}_{ij}\) is the shielding failure rate in strokes/100 km-year of mesh \(ij\) for the currents exceeding \(I_c\).
Fig. 4. Procedure for calculating the SFR of transmission lines with the proposed method.

\[ P(I) = \frac{1}{1 + \left( \frac{I}{31} \right)^{2.25}} \]  

where \( P(I) \) is the probability distribution function of the first stroke current exceeding \( I \) and is given by an equation such as (12) [27], [5]

\[ \text{TABLE II} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D )</td>
<td>430</td>
<td>M</td>
</tr>
<tr>
<td>( Sog )</td>
<td>9</td>
<td>M</td>
</tr>
<tr>
<td>( \alpha )</td>
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<td>M</td>
</tr>
<tr>
<td>( \beta )</td>
<td>20</td>
<td>M</td>
</tr>
<tr>
<td>( T_d )</td>
<td>15</td>
<td>days/year</td>
</tr>
<tr>
<td>Ground Wire Radius</td>
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<td>M</td>
</tr>
<tr>
<td>Phase Wire Radius</td>
<td>0.0158</td>
<td>M</td>
</tr>
</tbody>
</table>

\[ \text{TABLE III} \]

\[ \text{STRIKING DISTANCE EQUATIONS} \]

where \( I \) is the return stroke current in kiloamperes. The ground flash density (GFD) is assumed to be in the form of (13) and [28]

\[ \text{GFD} = 0.041 \times T_d^{1.25} \]  

where \( T_d \) is the number of thunderstorm days per year and GFD is the ground flash density (flash/km²-year).

Equation (12), which was originally used by [5] and [27], inherently assumes that the median return stroke current is 31 kA, which is the proper distribution when considering flashes.
to ground wires and towers [27], [29]. The authors in [30] have shown that lightning current distribution to ground with a median value of 24 kA may be more appropriate to calculate the shielding failure performance and slightly increases the SFR values. In this paper, as our main focus would be on comparing the calculated results, the original (12) is utilized. Nevertheless, for an actual calculation, it would be more accurate to use the ground-level current distribution [30].

In Table II and Fig. 6, the distances and dimensions are given. The total SFR is then calculated

$$\text{SFR} = 4 \sum_{i=1}^{m} \sum_{j=1}^{n} \text{SFR}_{ij},$$

In Fig. 7, the results for SFR calculation utilizing the proposed method are compared with EGM and different striking distance equations (for the 400-kV overhead line shown in Fig. 6 and $T_d = 15$ days/yr). The chart represents the SFR with respect to $I_c$, see (11). Using the charts, such as Fig. 7, enables us to represent the SFR value for any given stroke current. The max return stroke current attaching the phase wires is seen in this figure (i.e., the inception of curves with the horizontal axis) as well as the total SFR (i.e., the inception of curves with the vertical axis). With these charts, it is also possible to simply estimate the shielding failure flashover rate (SSFOR) for a given $I_c$, which is the critical return stroke current that the line insulation can still resist (i.e., $I_c = \frac{2 \text{CFO}}{Z_c}$, where CFO is the critical flashover rate of the line insulation, and $Z_c$ is the surge impedance of the line).

![Fig. 6. The 400-kV tower and dimensions.](image)

The striking distance equations in Fig. 7 are listed in Table III and are basically adopted from the review of striking distance equations in [29]. In this table, $I$ is the return stroke current, $h$ is the average ground wire height, and $y$ is the average phase wire height (i.e., the wire height at tower minus two-thirds of the midspan sag).

The Cooray et al. equation in Table III [8] is tuned for the strokes to flat ground, and considering the height of overhead lines, it might not be suitable for SFR calculation. Actually, for practical purposes, the return stroke current distribution to flat ground is suggested to be more appropriate for SFR calculation [30] which leads to a slightly higher value of SFR. Regarding the Cooray et al. striking distance equation [8], the same engineering philosophy could apply and, therefore, this equation is included in the comparisons. As can be seen from Fig. 7, the Cooray et al. striking distance equation, as expected, has predicted considerably higher SFR values.

Taking into account that the EGM curves in Fig. 7 are tuned for average wire height, the proposed method of SFR calculation has predicted total SFR which is higher than almost all of the EGM predictions. The SFR for the tower height of wires would be closer to the proposed method. Nevertheless, it must be noted that the agreement between SFR results obtained by different lightning attachment models may vary with transmission-line geometry.

The total SFR according to proposed method is lower than Cooray et al. [8] (which have predicted quite higher values of SFR in comparison with all of the other methods). From the $I_{\text{max}}$ point of view, Erikson’s [7] and Young’s [1] prediction are closer to the proposed LPM. Since all of the EGM approaches have similar trends in Fig. 7, the calculated SFR, according to the proposed method, shows higher sensitivity to return stroke currents. The SFR, according to the proposed method, is calculated from the summation in (14) for the results of simulation of all meshes of Fig. 5 and, hence, the max stroke current attaching the shield wires has affected by all configurations through the span which is not modeled by EGM and this could have affected the max stroke current attaching the phase wires. A comparison is also made between the effects of different upward leader cri-
teria on SFR values, see Fig. 8. The critical length [13], which is also used in [12], provides more similar results to the self-consistent model. According to this figure, the SFR versus stroke current curve shows similar trends for the simulated upward leader inception criteria while the numerical values are different. It can be deduced that the sensitivity of SFR to stroke current is governed less by the inception criteria. Nevertheless, the critical-length criterion predicts a higher value for SFR than the proposed method while the Rizk criterion predicts lower values for an identical configuration.

As discussed in Section II-C, modeling the wires by vertical and horizontal segmental line charges may cause errors in the results. The requirement is to presimulate each case to ensure that the number of sections on each wire are selected properly. In Table IV, the SFR value and simulation time are presented for different segmental line charges and for the tower configuration of Fig. 6 and $T_d = 15$ days/yr. The SFR value has considerable changes when the number of segments is set to lower values. However, with a large number of segments, the simulation shows converging nearly identical values for SFR. Nevertheless, the simulation time increases dramatically by increasing the number of segments. Hence, a preanalysis step is required to set the number of segments to ensure low errors and lowest possible simulation time.

Figs. 9 and 10 are a brief view of high computation volume which shows the SFR and maximum return stroke current incepting the phase wires (Fig. 6, $T_d = 15$ days/year) with respect to the shielding angle in different heights of phase wires, respectively. Using these charts, it is possible to choose the proper shielding angle in different heights to achieve specified lighting performance for a line with similar configuration. What is important about this figure is that the incremental height of the shield wire above the phase conductors for all shielding angles is kept constant during simulation (i.e., in each curve of Figs. 9 and 10, the shield wire location is changed on a horizontal line). Moreover, ring charge locations and the height of different parts of towers are adopted while changing phase and ground wires height. The SFR values computed by the proposed method seem to be less sensitive to the height of line conductors and more sensitive to the shielding angle in comparison with conventional EGMs [1], [2], [4], [5], [6]–[8].

While the curves in these figures are showing the changes in SFR and maximum return stroke current properly for positive shielding angles, they may be misleading for negative shielding angles. The SFR values and maximum return stroke current tend to increase for more negative shielding angles while in the real world, negative shielding angles actually improve the shielding performance of an overhead line. It is because, in practice, the incremental height of shield wires will change for different shielding angle designs and, therefore, the negative shielding angles improve the SFR values considerably. In the
Fig. 11. Simulated value of SFR and the field observation for the overhead lines listed in Table V.

The simulation performed to derive those curves, however, the incremental changes for the height of the shield wires are kept constant and this may result in higher SFR values (which is basically because the strokes tend to end the middle phase with this assumption). Hence, the negative shielding angle results are marked to not be applicable in these figures. Moreover, some real negative angle configurations are simulated, and calculated SFR values are compared with observation, see Table V and Fig. 11.

Nevertheless, the proposed LPM procedure has to be tested for some practical configurations to make a comparison between field data and simulation. Table V lists the statistics of the lightning performance of some observed overhead lines. The first ten overhead lines are adopted from the original data provided by reporting data units (DU) which are summarized in [31] and the data for last two overhead lines are adopted from [32]. In Fig. 11, the calculated SFR based on the proposed LPM is compared with field observations.

It is important to note here that the calculated SFR for the overhead lines of Fig. 11 is based on original $T_d$, which is given in Table V, and the original lightning stroke peak current distribution of (12). While data unit 39, 40, and 92 have reported low values of SFR, the simulations have predicted no flashover. Generally, the calculated SFR values are lower than observation and for huge structures of the “UHV Line,” the calculated value diverges considerably from observation. However, utilizing the ground-level peak stroke current distribution, [30] will increase the SFR values slightly.

Nevertheless, the simulation shows a general trend to agree with observation accepting the fact that it is not possible to achieve the exact results by simulation. In addition to the comparison of Fig. 11, the data provided in [32] for the number of strokes attaching each phase (the last two overhead lines of Table V) are utilized to make another comparison of the proposed LPM procedure with field data. Fig. 12 shows the percentage of strokes attaching each phase in calculation and observations. Here also, the simulation results generally agree with observations. However, the strokes percentage to middle phase is underestimated and the there are higher errors for the “UHV Line.”

V. CONCLUSION

In this paper, an alternate method for calculating the SFR of overhead transmission lines based on downward and upward lightning leader progression in three dimensions is presented. The procedure of calculating SFR is adopted from previous work [12] with some emphasis on cloud and tower models, downward leader charge density, and a self-consistent model for upward leader inception. A comparison is made between the results of the proposed method and EGM and between different upward criteria for stable leader inception. The SFR value from available observation data of some overhead lines is also compared with the predicted SFR value of the proposed method. The effect of shielding angle and tower height is also investigated under some simplifying assumptions.

From the simulation results, the SFR derived by the proposed method qualitatively agrees with conventional EGM; however, this agreement may vary for different transmission-line geometry. Nevertheless, the sensitivity of the SFR value to return stroke current is higher. While the proposed method creates a suitable environment to implement different upward connecting leader criteria, a comparison has been made between some of those criteria. This comparison revealed that SFR values versus return stroke current follow similar trends by those implemented
upward-connecting leader criteria but total SFR and max return stroke current attaching the phase wires are different. The comparison of the calculated SFR with the field observations also revealed that the proposed LPM procedure generally underestimates the actual values while for very large structures and high lightning activity, the estimations diverge from the observations. However, the simulation results generally agree with observations.

The need for calculating the electrical field by the charge simulation method in each computational step makes the procedure of this paper too time-consuming. The number of meshes, number of horizontal and vertical line charges modeling the wires, the range of return stroke current, height of tower and clouds, and maximum lightning leader steps all influence the processing time considerably. It is then better to choose the most applicable resolution for calculation. Taking into account the effects of conductor sags and physical behavior of lightning leaders requires full procedure computation and, thus, takes long simulating time. Nevertheless, it is almost always possible in design stages and for long-term planning purposes to perform such time-consuming analysis.

ACKNOWLEDGMENT

The authors would like to thank Dr. H. Gharagozloo from IGMC and N. Mirtajaddini and F. Azinfar from KREC for their kind discussions. The authors would also like to thank M. Karimi from TAVANIR for providing the necessary data of overhead lines.

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