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Performance of Large-Scale Grounding Systems in Thermal Power Plants Against Lightning Strikes to Nearby Transmission Towers

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Abstract—In spite of the contemporary interest in renewable power plants, thermal power plants are still inevitable. Various electric equipment and apparatus are grounded via a large-scale grounding system in thermal power plants. In this paper, the three-dimensional finite-difference time-domain method has been employed to study the performance of such a large-scale grounding system against a lightning strike to a nearby transmission tower. The study has emphasized how a nearby sea, which is utilized for cooling purposes in thermal power plants, influences the ground potential rise on the large-scale grounding system considering soil ionization. The results show that the distribution of the ground potential rise on the large-scale grounding system is quite dependent on the alignment of sea with the large-scale grounding system. In addition, the extent that soil ionization affects the ground potential rise is dependent on the distance between the struck tower and the large-scale grounding system.

Index Terms—Electromagnetic fields, finite-difference time-domain (FDTD) method, grounding systems (GSs), lightning strikes.

I. INTRODUCTION

THE GLOBAL interest in renewable energy is currently increasing due to environmental considerations. However, the majority of the contemporaneous electric energy consumed all over the world is actually produced from thermal power plants owing to the intermittent nature of renewable resources and their associated technical challenges [1]. Power system apparatus, equipment, and electric circuits inside a thermal power plant are grounded by a large-scale grounding system (LSGS) to protect them against power system electromagnetic transients such as lightning and switching surges. Therefore, a considerable research has been devoted to study grounding systems (GSs) [2], [3]. Effective design fundamentals of different GS configurations have been addressed [4], [5]. Moreover, the frequency dependence of soil parameters has been considered for the lightning response of grounding electrodes [6], [7]. Furthermore, the finite-difference time-domain (FDTD) method has been employed to study how the ground potential rise (GPR) spreads between two grounding electrodes in [8]. Recently, a design of a GS has been presented for substations considering inhomogeneous soil [9]. A measuring touch/step voltage technique is presented in [10] for GSs in substations. The high-frequency behavior of GSs has been considered to estimate the stress of the arresters [11].

The influence of soil inhomogeneity, in terms of both horizontal and vertical stratification of the ground, on lightning electromagnetic fields has been intensively investigated within the last few years, where the results exhibit such an influence to be quite significant [12]–[20]. In fact, not only soil inhomogeneity but also the phenomenon of soil ionization affects, in particular, the lightning response of GSs. Therefore, a considerable effort has been devoted to model this phenomenon and investigate its impact on the lightning response of GSs [21]–[24].

Due to the widespread of thermal power plants all over the world and since they are typically constructed close to a water body (e.g., sea or lake) for cooling purposes, we think that the lightning response of their LSGS still requires further investigation and analysis. Based on the above, important factors influence considerably the lightning response of those LSGS, such as the inhomogeneous resistivity because of the different media in ground and soil ionization associated with high electric fields around grounding electrodes. Furthermore, low-voltage control and communication circuits inside thermal power plants may be relatively long and, hence, grounded at different points of the LSGS. Accordingly, it is worth to analyze the performance of LSGSs against lightning strikes, as those circuits are quite vulnerable to lightning surges.

In this paper, transient electromagnetic fields are computed for the LSGS of a thermal power plant due to a lightning strike to a nearby grounded transmission tower, TWR, using the 3-D FDTD method. The nonlinearity and inhomogeneity of soil resistivity due to ionization and the different media composing the ground are considered. After introducing why such investigations are implemented in Section I, the adopted case studies
and the employed methodology to compute the electromagnetic transients are elaborated in Section II. Section III shows and analyzes the results of these computed electromagnetic transients, whereas their influence on relatively long circuits is discussed in Section IV. Finally, Section V explores the conclusions of this study. It is worth to mention that the back flashovers at the LSGS of each Twrs are exploded and filled by a sand for the construction purposes. The power plant is supposed to be on a rocky land so that the ground surface has an intermediate resistance. As aforementioned, the thermal power plant is constructed close to a sea for cooling. A return stroke is assumed to strike one of those Twrs that are connected together and to the gantry of the power plant via shielding wire, and the gantry is solidly connected to the LSGS.

II. CASE STUDY AND METHODOLOGY

An LSGS of a thermal power plant is considered with the closest two Twts of the transmission system. The power plant is supposed to be on a rocky land so that the ground surface has been exploded and filled by a sand for the construction purposes. As aforementioned, the thermal power plant is constructed close to a sea for cooling. A return stroke is assumed to strike one of those Twts that are connected together and to the gantry of the power plant via shielding wire, and the gantry is solidly connected to the LSGS.

A. Case Study

Two case studies, CS1 and CS2, are conceived regarding the position of the nearby sea, where it is located on the $y^+$ and $x^+$ sides of the LSGS for CS1 and CS2, respectively, as shown in Fig. 1. In addition, two striking scenarios, SC1 and SC2, are considered for each of CS1 and CS2, where the lightning strikes the first Twr, Twr1, for the SC1, as seen in Fig. 1, whereas the second Twr, Twr2, is struck in SC2. Fig. 1 shows that both horizontal stratification and vertical stratification of the ground are included in this study owing to the existence of rock, sand, and sea, as illustrated before. The electrical properties for such different media are adopted as follows: the resistivity $\rho = 2500$, 20,000, and 0.25 $\Omega \cdot m$, whereas the relative permittivity $\varepsilon_r = 10$, 4, and 40 for sand, rock, and sea, respectively. In fact, this work considers such values as the rocky ground has typically high $\rho$ and low $\varepsilon_r$ like the case in Nordic countries.

In Fig. 1, the radii of shield wires and grounding electrodes are, respectively, 0.004 and 0.01 m. The GS of each Twr has four vertical electrodes of 8 m in length and connected together under 4 m of the ground surface via horizontal electrodes. The LSGS consists of three layers of connected horizontal and vertical electrodes, where each electrode is separated by 10 m from the next parallel one. The LSGS dimensions are $130 \times 200 \times 8$ m$^3$ in the $x^+$, $y^-$, and $z$-axes, respectively, where the upper layer of the LSGS is at 2 m under the ground surface.

Two first stroke waveforms, FRS1 and FRS2, are adopted for the study, where FRS1 has a single peak, while FRS2 has a double peak. Both FRS1 and FRS2 have a velocity of 120 m/$\mu$s and rise to a peak $I_p$ of 100 kA within a rise time $T_s = 6.5$ and 11.5 $\mu$s, respectively. Fig. 2 shows lightning current $I_{RS}$ of both first stroke waveforms associated with their first time derivatives, $di/dt$. FRS1 and FRS2 have been conceived from the statistical observations of real lightning strokes to transmission towers shown in [25], where they are well compatible with cumulative probabilities of $I_p$, $T_s$, and $di/dt$.

Because of the high values of $\rho$ adopted in this study, the ionization and deionization phenomena have been taken into account. Basically, when the electric fields produced around the grounding electrodes exceed a critical intensity, $E_i$, small air gaps between the soil particles around the electrodes start to ionize, and consequently, the equivalent $\rho$ of the soil decreases. As long as the electric field intensity is higher than $E_i$, the ionization process continues and the equivalent $\rho$ of the soil decreases more. On the other hand, such an ionization process stops when the electric field intensity becomes less than $E_i$, and subsequently, the equivalent $\rho$ of the soil increases to restore its original value before the ionization, where such a case is known by the deionization process [21], [22].

B. Methodology

FRS1 and FRS2 have been modeled by the Heidler function (1) [26]. Heidler coefficients of both adopted current waveforms are obtained and given in Table I following the presented...
approach in [27]. Furthermore, the stroke channel has been modeled using the transmission line model [28]

\[ I_{RS}(t) = \frac{1}{\eta_k} \sum_{k=1}^{K} \left( \frac{I_{0k}}{\eta_k} \cdot \exp \left( -\frac{t}{\tau_{2k}} \right) \cdot \left( \frac{t}{\tau_{1k}} \right)^{n_k} \right) \]

where \( \eta_k = \exp \left( -\left( \frac{t}{\tau_{1k} \cdot \tau_{2k}} \right) \cdot (n_k - \tau_{2k} / \tau_{1k}) \right) \).

The 3-D FDTD method has been employed for this study to solve both Maxwell’s curl equations, (2) and (3), numerically in the time domain. In fact, this method is quite advantageous in representing the inhomogeneous media of this study, as elaborated in Section II-A. Furthermore, the FDTD method tackles flexibly the ionization and deionization phenomena in the time domain without the need for predicting a specific volume of the ionized soil. Basically, the algorithm presented by Yee has been implemented to divide the solution space into orthogonal cells and position the electromagnetic fields within these cells along the Cartesian coordinates according to (2) and (3), whereas the electric and magnetic fields are alternatively updated following the Leapfrog approach [29]–[31]. Since the solution space, shown in Fig. 1, is relatively large, it has been nonuniformly divided, as elaborated in [30]. The electric fields located on the six boundary planes are differentially extrapolated using Liao second-order absorbing boundary conditions [32]. The shield wires and grounding electrodes are modeled using the thin-wire models illustrated in [33] and [34]. The shield wires are connected to the left absorbing boundary plane to avoid reflections [35]. Ultimately, the GPR and currents waveforms are, respectively, calculated by the line integral of the computed electric fields on the ground surface and using the Ampere law for the computed magnetic fields

\[ \nabla \times \mathbf{E} = -\mu \cdot \left( \partial \mathbf{H} / \partial t \right) \]  

(2)

\[ \nabla \times \mathbf{H} = \sigma \cdot \mathbf{E} + \epsilon \cdot \left( \partial \mathbf{E} / \partial t \right) \]  

(3)

where \( \mathbf{E} \) and \( \mathbf{H} \) are the electric and magnetic field vectors; \( \mu, \sigma, \) and \( \epsilon \) are the permeability, conductivity, and permittivity of the medium, respectively; and \( \partial / \partial t \) is the time-derivative operator.

In order to consider the ionization and deionization of soil in the 3-D FDTD method, \( \rho \) of each cell inside the soil has become a function of time depending on the resultant electric field \( E = \sqrt{E_x^2 + E_y^2 + E_z^2} \) of the cell. The critical intensity of \( E \) to initiate ionization is taken as \( E_i = 300 \) kV/m. Thus, a cell inside soil ionizes, and its \( \rho(t) \) decreases gradually as given by (4) for \( E \geq E_i \), assuming ionization time constant, \( \tau_i = 2 \) μs. The ionization process continues in such a cell as long as \( E \geq E_i \) till its \( \rho(t) \) reaches its minimal value \( \rho_i \) when \( E = E_i \) at the end of the ionization. Afterwards, the deionization process begins as an ionized cell inside soil deionizes to restore its original value of \( \rho(t) \), \( \rho_0 \), gradually as given by (5) for \( E < E_i \) assuming deionization time constant, \( \tau_d = 4.5 \) μs [21], [22]

\[ \rho(t) = \rho_0 \cdot \exp \left( -t / \tau_i \right) \]  

(4)

\[ \rho(t) = \rho_i + (\rho_0 - \rho_i) \cdot \left( 1 - \exp \left( -t / \tau_d \right) \right) \cdot \left( 1 - E / E_i \right)^2 \]  

(5)

III. RESULTS AND ANALYSIS

The FDTD algorithm has been coded in the MATLAB platform, where the computer specifications are Intel Core i7-6700 with a 16-GB RAM. The computational time for a case including soil ionization is 5 h, and it becomes 2 h without ionization.

From the computed electric fields using the 3-D FDTD method, the GPR waveforms have been computed at points \( P_1, P_2, \) and \( P_3 \) of the LSGS as well as the two GSS of \( T_{WR1} \) and \( T_{WR2} \), as shown in Fig. 1. In addition, the current \( I_{SW} \) flowing through the bases of both \( T_{WR1} \) and \( T_{WR2} \) has been calculated from the computed magnetic fields in addition to the flowing current \( I_{SW} \) through the shield wires of the transmission system. As illustrated in Fig. 1, \( I_{SW} \) has been computed within the shield wires section from \( T_{WR1} \) to \( T_{WR2} \) and also the section from \( T_{WR1} \) to the gantry.

Fig. 3 shows the calculated GPR waveforms for \( T_{WR1} \) and \( T_{WR2} \) due to FRS1 and FRS2 considering SC1 and SC2. It could be observed that FRS3 having shorter \( T_s \) results in a higher GPR. Moreover, the soil ionization causes a decrease in the GPR due to the reduction in \( \rho \) of soil. For instance, the maximum values of the calculated GPR at \( T_{WR1} \) and \( T_{WR2} \) have, respectively, decreased by 3.8% and 6% due to soil ionization for FRS1, and also by 2.7% and 5% for FRS2. The GPR waveforms calculated at \( P_1, P_2, \) and \( P_3 \) due to FRS1 and FRS2 are presented in Fig. 4 considering SC1 and SC2. It is found that the influence of soil ionization on these GPR waveforms is quite slight. Moreover, the magnitudes of the GPR at \( P_1, P_2, \) and \( P_3 \) for FRS1 are almost the same as their corresponding for FRS2. Furthermore, the GPR distribution on \( P_1, P_2, \) and \( P_3 \) of the LSGS is nonuniform for either FRS1 or FRS2.

<table>
<thead>
<tr>
<th>Table I</th>
<th>Heidler’s Coefficients for FRS1 and FRS2</th>
</tr>
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<tbody>
<tr>
<td>( k )</td>
<td>( I_{0k} ) (kA)</td>
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<tr>
<td>1</td>
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<tr>
<td>2</td>
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<td>6</td>
<td>35.2</td>
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<td>7</td>
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</table>
Fig. 4. GPR on $P_1$, $P_2$, and $P_3$ due to (a) FRS1 and (b) FRS2 for CS1 and SC1. (— and - - - - without and with ionization.)

Fig. 5. $I_{Base}$ due to (a) FRS1 and (b) FRS2 for CS1 and SC1. (— and - - - - without and with ionization.)

Fig. 6. $I_{SW}$ due to (a) FRS1 and (b) FRS2 for CS1 and SC1. (— and - - - - without and with ionization.)

Fig. 7. GPR on TWr1 and TWr2 due to (a) FRS1 and (b) FRS2 for CS1 and SC2. (— and - - - - without and with ionization.)

Fig. 8. GPR on $P_1$, $P_2$, and $P_3$ due to (a) FRS1 and (b) FRS2 for CS1 and SC2. (— and - - - - without and with ionization.)

Fig. 9. $I_{Base}$ due to (a) FRS1 and (b) FRS2 for CS1 and SC2. (— and - - - - without and with ionization.)

Fig. 10. $I_{SW}$ due to (a) FRS1 and (b) FRS2 for CS1 and SC2. (— and - - - - without and with ionization.)

Fig. 11. GPR on TWr1 and TWr2 due to (a) FRS1 and (b) FRS2 for CS2 and SC1. (— and - - - - without and with ionization.)

Fig. 5 shows the calculated $I_{Base}$ for TWr1 and TWr2 due to both FRS1 and FRS2 considering the SC1 and CS1. In addition, Fig. 6 shows the calculated $I_{SW}$ through the two portions, between TWr1 and TWr2 and between TWr1 and the gantry, of the power plant. It could be observed from both Figs. 5 and 6 that the soil ionization causes an increase in $I_{Base}$ and, consequently, a decrease in $I_{SW}$ entering the gantry and, subsequently, the LSGS through the gantry. It is also deduced from these figures that most of $I_{RS}$ flows through the shield wires portion between TWr1 and the gantry due to the LSGS.

Figs. 7–10 are, respectively, the same as Figs. 3–6 but for SC2. It is inferred from comparing Figs. 7–10 with Figs. 3–6 that the impact of soil ionization becomes more significant for SC2 than SC1. The maximum values of the computed GPR at TWr1 and TWr2 have, respectively, decreased by 18% and 13% due to soil ionization for FRS1, and by 17% and 12% for FRS2. This is because TWr2 is farther located from the LSGS, and subsequently, higher current flows through TWr2, resulting in higher electric fields around its GS for SC2. In addition, it is found that the computed $I_{Base}$ for TWr2 increases significantly due to such a considerable ionization of the soil around its GS for SC2. Thereby, $I_{SW}$ entering the LSGS through the gantry decreases considerably, thus resulting in lower magnitude of the GPR calculated at $P_1$, $P_2$, and $P_3$. Similar to SC1, the magnitudes of the GPR waveforms at $P_1$, $P_2$, and $P_3$ are different for SC2 with both FRS1 and FRS2. Ultimately, it is inferred that the GPR is nonuniform on the LSGS for CS1 irrespective of the struck TWr, $I_{RS}$, and soil ionization.

Figs. 11–18 present the corresponding waveforms of those shown in Figs. 3–10, respectively, but for CS2 depicted in Fig. 1(b). Considering SC1, it is found from Fig. 11 that the maximum values of the computed GPR at TWr1 and TWr2 have, respectively, decreased due to soil ionization by 3.8% and
that the influence of soil ionization on GPR, $P_1$, $P_2$, and $P_3$ due to (a) $FRS_1$ and (b) $FRS_2$ for $CS_2$ and $SC_1$. ($\cdots$ and $\cdots$ $\Rightarrow$ without and with ionization.)

It is observed from the sea side (i.e., parallel to the sea side) so that the sea side, which represents a highly conductive surface, forces the closer points to it so the GPR at $P_2$ becomes surely more significant for $SC_2$ as compared to $SC_1$. Thereby, it is inferred that the reduction in the maximum values of the computed GPR waveforms becomes greater and more significant with the closer points to the sea considering $CS_2$ and their corresponding magnitudes for $CS_1$ become greater and more significant as noticed by comparing Figs. 12 and 16, respectively, with Figs. 4 and 8. Moreover, the differences between these GPR magnitudes for $CS_2$ and their corresponding magnitudes for $CS_1$ are located along the $x$-axis; since the sea is located on the $y$-axis so that their GPR waveforms are calculated by the line integral of the FDTD-computed perpendicular electric fields along the $x$-axis; such a behavior of the current flowing out of the LSGS results in lower electric fields along the $x$-axis, and consequently, the calculated GPR waveforms get lower. In fact, such an impact of the sea on the calculated GPR waveforms becomes surely more significant for the closer points to it so the GPR at $P_3$ is maximally influenced, then the GPR at $P_2$, and, finally, at $P_1$. This observation is interpreted as follows: $P_1$, $P_2$, and $P_3$ are located along the $y$-axis so that their GPR waveforms are calculated by the line integral of the FDTD-computed perpendicular electric fields along the $x$-axis; since the sea is located on the $y^+$-direction of the LSGS for $CS_1$, then a considerable amount of the current flowing out of this GS tends to flow along the $y$-axis toward the sea side; such a behavior of the current flowing out of the LSGS results in lower electric fields along the $x$-axis, and consequently, the calculated GPR waveforms get lower.

$E_x = \sqrt{E_x^2 + E_y^2}$ on the ground surface due to $FRS_1$ at 7 and
21 μs for CS₁ and SC₁ considering soil ionization. It is shown from Fig. 19 that the distance between Twr₁ and Twr₂ is 240 m that conforms to Fig. 1. It is inferred from the figure that \( E_r \) on the ground surface inside the LSGS is zero because it is an equipotential surface. The maximal intensities of \( E_r \) are 490 and 140 kV/m at 7 and 21 μs, respectively. The intensity of \( E_r \) on the ground surface is descendingly graded from the LSGS and GSs of both TwrS to outside. The boundary conditions at the interfaces between different media, such as rock–sand and rock–sea, on the ground surface are verified. These boundary conditions are the continuity of the tangential electric field and perpendicular current density at the boundary. Since the sea is located on the \( y^+ \)-direction of the LSGS for CS₁, the \( E_x \) components in the rock at the rock–sea boundary are forced to be zero owing to the continuity of the tangential electric field. On the other hand, the intensity of \( E_y \) components in the rock at the rock–sea boundary becomes considerably high owing to the continuity of the perpendicular current density as most of the current tends to flow toward the sea owing to its high \( \sigma \). The boundary conditions are also verified at the rock–sand interface as shown around the LSGS in Fig. 19(b).

Fig. 20 shows the ionized area of soil on the ground surface due to FRS₁ at 7 and 21 μs considering CS₁ and SC₁. Owing to the different media on the ground surface (i.e., rock, sand, and sea), the ionized area is presented as a per-unit value of its original value before ionization, where \( \rho_{pu} = \frac{\rho}{\rho_0} \). It could be observed from Fig. 20 that the soil has ionized around the GSs of both TwrS unlike the LSGS. This is attributed to the fact that the current flows out of such an LSGS; it flows across a considerably large area, which results in low current density and, subsequently, low electric fields that are not sufficient and too low to cause soil ionization around the LSGS. The minimal values of \( \rho_{pu} \) on the ground surface are 0.56 and 0.7 at 7 and 21 μs, respectively. In Fig. 19, it could be deduced from the color bar that the electric field intensity on the ground surface at Twr₁ becomes lower than \( E_i \) so that the soil surrounding the GS of Twr₁ is deionizing at 7 μs and its \( \rho \) is increasing toward \( \rho_0 \). On the contrary, the electric field intensity on the ground surface at Twr₂ is higher than \( E_i \) so that the soil surrounding the GS of Twr₂ is ionizing at 7 μs and its \( \rho \) is decreasing. In addition, the electric field intensities on the ground surface at Twr₁ and Twr₂ are lower than \( E_i \) at 21 μs. Therefore, the minimal computed \( \rho_{pu} \) on the ground surface at 21 μs is greater than its corresponding one at 7 μs, as the soil is entirely deionizing at 21 μs. Ultimately, Figs. 19 and 20 exhibit conformance as both ionization and deionization processes are compatible with the electric field intensity. In order to further clarify the extension of the ionized area of soil on the ground surface, the ionized areas of soil around the GSs of Twr₁ and Twr₂ have been zoomed in the same figure, as shown in Fig. 20. It could also be noticed from Fig. 20 that the ionized area at Twr₁ shrinks with the passage of time as the soil is deionizing at 7 μs and beyond.

Figs. 21 and 22 are, respectively, the same as Figs. 19 and 20, but for SC₂. In Figs. 21 and 22, the maximal intensities of \( E_r \) are 480 and 97 kV/m, while the minimal \( \rho_{pu} \) are 0.28 and 0.63 at 7 and 21 μs, respectively. The comparison between Figs. 19 and 21 shows that the area of \( E_i \) exceeding \( E_i \) at the struck Twr is wider for SC₂ as compared to SC₁. This is because the current reaches the LSGS through the gantry for SC₁ much faster as compared to SC₂. Therefore, a greater amount of \( I_{RS} \) flows through the GS of Twr₂ in SC₂ as compared to that flows through the GS of Twr₁ in SC₁. In addition, it is particularly inferred from Fig. 21 that the boundary conditions at the rock–sand and rock–sea interfaces are verified. It is deduced from Figs. 20 and 22 that the ionized area of soil at the GS of the struck Twr is wider for SC₂ as compared to SC₁. In addition, the minimum value of \( \rho_{pu} \) for SC₂ is considerably lower than that for SC₁. In fact, the wider ionized area of soil and also the lower value of the minimum \( \rho_{pu} \) are attributed to the aforementioned greater amount of \( I_{RS} \) flowing through the GS of Twr₂ and the consequent higher electric fields for SC₂. Actually, such observations obtained from Figs. 20 and 22 reflect the greater influence of soil ionization on the computed GPR and current waveforms considering SC₂ as compared to SC₁, as presented.
before. It is also noticed from Fig. 22 that the ionized area of soil shrinks and $\rho_{pu}$ increases with time passage due to the soil deionization.

Figs. 23 and 24 are, respectively, similar to Figs. 19 and 21, but for CS$_2$ rather than CS$_1$. In Fig. 23, the maximal intensities of $E_r$ are, respectively, 490 and 160 kV/m at 7 and 21 $\mu$s, whereas their corresponding values are 480 and 105 kV/m in Fig. 24. Indeed, comparable observations are obtained from Figs. 19, 21, 23, and 24, while Figs. 23 and 24 differ from Figs. 19 and 21 regarding that $E_r$ is no longer symmetrical with respect to mid-distance of the $x$-axis because the sea is located on the sea side of the LSGS. Accordingly, Figs. 23 and 24 show obviously that the intensity of $E_r$ at the LSGS side facing the sea becomes greater as compared to the other side. This is justly due to that most of the current entering the LSGS tends to flow toward the sea because of its high $\sigma$.

The ionized area of soil on the ground surface for CS$_2$ has not been presented because it is identical to that for CS$_1$ shown in Figs. 20 and 22. This is due to that the GSs of TwT$_1$ and TwT$_2$, where the soil ionization happens, are sufficiently far from the sea side so that the electromagnetic fields in the vicinity of both GSs are not influenced by the reflections of the electromagnetic fields occurring at the sea–rock boundary.

IV. DISCUSSION

This section discusses how different nonuniform and uniform GPR distributions on an LSGS affect the electrical stresses imposing a long low-voltage circuit having multigrounding points. As shown in Figs. 4, 8, 12, and 16, the GPR distribution is nonuniform for CS$_1$, while it is uniform for CS$_2$. Fig. 25 shows a long circuit of an aerial cable having $l$, $r_1$, $r_2$, $r_3$, $r_4$, $100$, 0.0022, 0.004, 0.0044, 0.0048 m and $\epsilon_r = 4$ of the main insulator, $Ins.1$, whereas its ends are grounded to $P_1$ and $P_2$ of the LSGS. Such a circuit has been modeled deeming the frequency dependence for the cable parameters and its transformation matrix in an EMTP software. The GPR waveforms computed at $P_1$ and $P_2$ by the 3-D FDTD method considering soil ionization have been exported to both controlled voltage sources of the circuit so that these sources exactly represent the GPRs at $P_1$ and $P_2$. A step voltage of 32 V is applied at the sending end of the cable, while the receiving end is matched by 20 $\Omega$; such a configuration practically emulates a communication/control circuit between the protective devices or control center and the switchgear in power plants. Those electrical stresses are investigated in terms of the build-up voltage between the core and sheath (i.e., voltages across $Ins.1$) at both ends and the mid-point. Figs. 26 and 27 present the build-up voltages for SC$_1$ and SC$_2$, respectively, due to FRS$_1$ and FRS$_2$ at the sending end, $V_s$, mid-point, $V_m$, and the receiving end, $V_r$. These build-up voltages are shown in solid and dashed lines for SC$_1$ and SC$_2$, respectively. Figs. 26 and 27 show that $V_m = 32$ V for both CS$_1$ and CS$_2$. Moreover, it is obviously inferred that the nonuniform GPR distribution on the LSGS for CS$_1$ results in considerably higher $V_m$ and $V_r$, as compared to the uniform GPR distribution for CS$_2$. It is also worth to mention that the nonuniform GPR distribution on the LSGS does not cause high risk of failure for $Ins.1$, but also results in an increasing current through the cable sheath due to the potential difference between its two ends.

In [6], a dispersion of soil parameters has been reported, whereby $\sigma$ increases and $\epsilon$ decreases with high-frequency components of the lightning current. Thereby, neglecting such frequency dependence of soil may overestimate the electric field at the ground level and, subsequently, indicate inaccurate
prediction of soil ionization, particularly for highly resistive soil [36]. Since the studied system includes quite high values of \( \rho \), the frequency spectrum of FRS1 and FRS2 has been computed using the fast Fourier transform. The \( \text{rms} \) value of each frequency component, \( I_{\text{rms}} \), is presented as a ratio of the \( dc \) component, \( I_{dc} \), in Fig. 28. It is inferred that \( I_{\text{rms}} \) for frequency components \( >10^4 \) Hz is considerably low. Since \( \sigma \) varies slightly over a range up to around \( 10^4 \) Hz [6], we expect that such frequency dependence does not significantly affect the computation accuracy. Furthermore, the studied system is too complicated to include the frequency dependence of soil parameters due to the electromagnetic reflections between the Twr and its GS, the interactions between the Gs of the Twrs and the LSGs, and the nonlinearity and inhomogeneity of soil.

V. CONCLUSION

The response of an LSGS of a thermal power plant has been tackled for lightning strikes to nearby transmission towers, Twrs. The Twrs are connected to the LSGs via shield wires and the plant gantry. The impacts of nearby sea, distance between the struck Twr and the LSGs, and soil ionization on such a lightning response have been considered. The results reveal a remarkable impact of sea on the propagation of electromagnetic fields through the LSGs and, subsequently, the distribution of the GPR on the LSGs owing to its high conductivity. It is also inferred that low-voltage control and communication circuits, having multigrounding points of the LSGs, are liable to nonuniform GPR distribution that causes destructive effects. Accordingly, it is recommended for the grounding points of such circuits to be parallel to the sea side for uniform GPR distribution at those points so as to avoid severe electrical stresses. The results show that the soil around the Gs of Twrs is potentially exposed to ionization unlike that in the LSGs vicinity. Soil ionization causes a decrease in the soil resistivity and, subsequently, the computed GPR. The farther the struck Twr is from LSGS, the ionization impact on the GPR and currents waveforms becomes more significant.

REFERENCES


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