# Impact of Ocean-Land Mixed Propagation Path on Equivalent Circuit of Grounding Rods

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***Abstract*— In this paper, the effect of ocean-land mixed propagation path on the lightning performance of grounding rods is investigated. This effect is focused on two problems. The first is extracting exact equivalent circuit of grounding rods in the presence of oceans. The equivalent circuit can be used in transient analysis of power systems in the neighboring oceans. In the second one, this effect on the grounding potential rise (GPR) is investigated. Using the obtained GPRs, the effective length of vertical rods under such an effect can be easily investigated. The simulation results show that for grounding rods far from the ocean, i.e. greater than 15 m, such an effect can be disregarded.**

***Index Terms*—** Ocean-land mixed path, equivalent circuit, grounding potential rise.

## I. INTRODUCTION

Lightning performance of grounding systems with the intension of removing any damage to people and installations is of importance [1]. Fig. 1 shows schematic diagram of a typical grounding rod buried in homogenous soil (constant electrical parameters) under lightning stroke.

Transient voltage of grounding system (defined electrical potential of the grounding electrodes with respect to a reference point at infinite) is of great practical importance because of two reasons. Firstly it is able to reveal the maximum voltage level that is submitted to the ground. Secondly it is evaluates the time that the ground is subjected to certain levels of transient voltage. Safety criteria are based upon minimizing this parameter. It should be thus correctly computed. This parameter is usually computed via EMTP (Electromagnetic Transient Program) software [2] through importing grounding system as equivalent circuit into EMTP. There are a number of equivalent circuits for the grounded electrodes [3] in homogenous soils as shown in Fig. 2. The values of R, L, and C in Fig. 2 are

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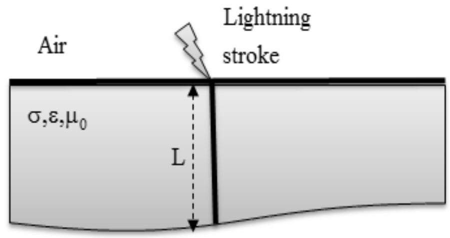
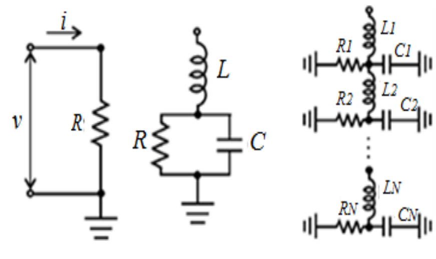
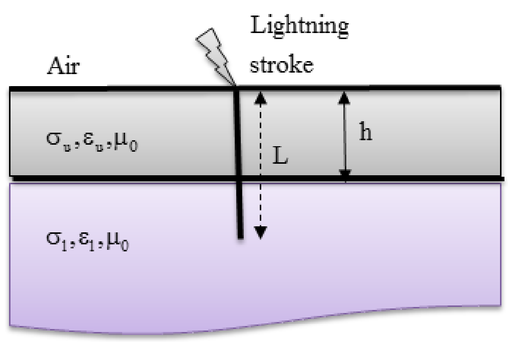



Fig. 1. A schematic diagram of a grounding vertical rod buried in homogenous soil.

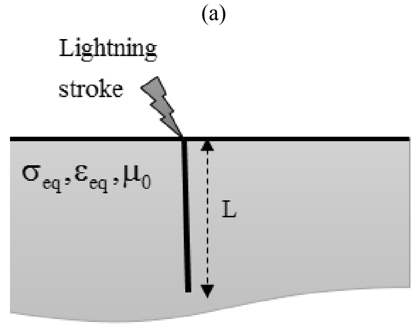



(a) (b) (c)

Fig 2. Circuit Models of the grounding vertical rod buried in homogenous soil. (a) resistivity model, (b) RLC model, and (c) high frequency RLC model.




(a)




(b)

Fig. 3. (a) A typical rod buried (a) in horizontally two-layered soil, and (b) in equivalent homogenous soil.

expressed in (1)-(3). These models, however, are valid for slow waveform current containing low frequency content such as first stroke current. However, for fast waveform currents such as subsequent stroke containing high frequency content, modified RLC model [4, 5] or the vector fitting method (VF) in combining with least square technique [6] can be used.

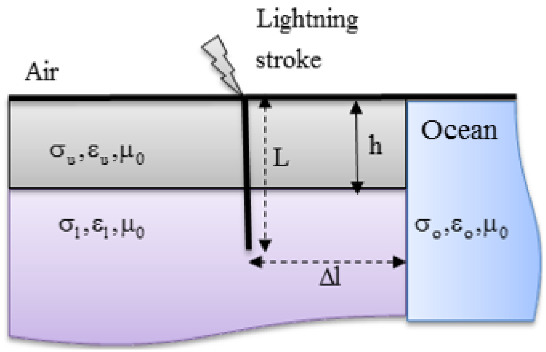



Fig. 4. A vertical rod buried in horizontally two-layered soil in the neighboring of an ocean.

$$R = \frac{\rho}{2\pi l}\left[\ln\left(\frac{4l}{a}\right) - 1\right](\Omega) \tag{1}$$

$$C = 2\pi\varepsilon l \Big/ \left[\ln(\frac{4l}{a}) - 1\right](F) \tag{2}$$

$$L = \frac{\mu_0 l}{2\pi}\left[\ln\left(\frac{2l}{a}\right) - 1\right](H) \tag{3}$$

It is well known that in some areas, the soil is non-homogenous, for instance horizontally two-layered soils as shown in Fig. 3(a). In this figure, the conductivity and relative permittivity of the upper and down layers are denoted by $(\sigma_u, \varepsilon_{ru})$ and $(\sigma_d, \varepsilon_{rd})$ respectively. Also, $h$ is the thickness of the upper layer. In such soils, the mentioned equivalent circuits cannot be used. To remove this restriction, the equivalent conductivity/resistivity approximation [7] can be used as shown in Fig. 3(b). Such an approximation, however, is valid only in the absence of oceans. In cases where horizontally two-layered soils are interfaced with oceans as shown in Fig. 4, this approximation is violated, and full-wave techniques such as finite element method (FEM) should be used [9-11].

To the best our knowledge, there is no research on the impact of such soils on wide-band equivalent circuit and accordingly transient analysis of vertical rods. Therefore, in this study the input impedance of a vertical rod is first computed using FEM, and then equivalent circuit is extracted using VF method [6, 7]. Importing this circuit into EMTP, grounding potential rise (GPR) is easily computed, and finally the ocean effect on the effective length can be accordingly inferred.
This paper is orgenized as follows. In section II, the principles of VF method in combining with least square technique is briefly introduced. Section III is focused on extracting VF-based equivalent circuit in the presence of oceans and transient analysis of vertical rods buried in such complex soils. Finally, concluding remarks are given in section IV.

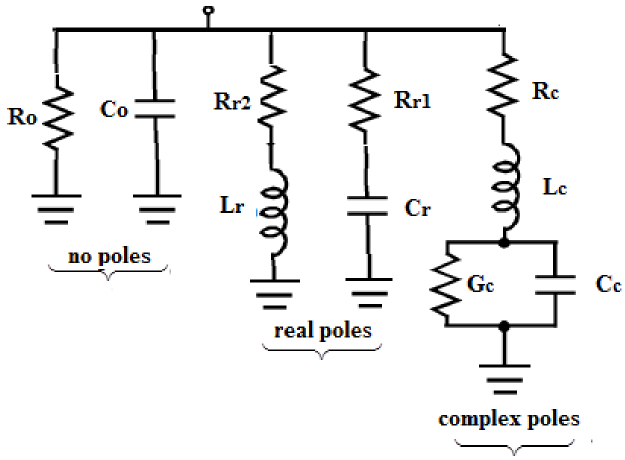



Fig. 5. General equivalent circuit proposed by vector fitting method (VF).

## II. VECTOR FITTING IN COMBINING WITH LEAST SQUARE

Extracting equivalent circuit of an electrical network is based on approximating frequency response, $f(s)$ with rational functions with the following form

$$F(s) = \sum_{n=1}^{N} \frac{c_n}{s-a_n} + d + sh \tag{4}$$

Where residues $c_n$ and poles $a_n$ are either real quantities or come in complex conjugate pairs, while $d$ and $h$ are real. The aim is to approximate these coefficients accurately. Also note that the equation (4) is a nonlinear problem versus the unknown coefficients. Vector fitting method (VF) in combining least squre technique solves this problem as a linear problem under assumption of known poles in an iteration process [6] as follows.

$$\left(\sum_{n=1}^{N} \frac{c_n}{s-a_n} + d + sh\right) - \left(\sum_{n=1}^{N} \frac{\tilde{c}_n}{s-a_n}\right) f(s) = f(s) \tag{5}$$

For a given frequency $s_k \ (k = 1,2,..N)$, we get

$$A_k x = b_k \tag{6}$$

Where

$$A_k = \begin{bmatrix} \frac{1}{s_k - a_1} & \cdots & \frac{1}{s_k - a_N} & 1 & s_k & -\frac{f(s_k)}{s_k - a_1} & \cdots & -\frac{f(s_k)}{s_k - a_N} \end{bmatrix} \tag{7}$$

$$x = \begin{bmatrix} c_1 & \cdots & c_N & d & h & \tilde{c}_1 & \cdots & \tilde{c}_N \end{bmatrix}^T \tag{8}$$

$$b_k = f(s_k) \tag{9}$$

Table 1. Computing the parallel branches in Fig. 3.

| **Poles and Residues** | **Parallel branch** | |
|---|---|---|
| $a_n$ (real)<br>$c_n$ (possitive-real) | $R_{r2} - L_r$ | $R_{r2} = -a_n / c_n$ , $L_r = 1/c_n$ |
| $a_n$ (real)<br>$c_n$ (negative-real) | $R_{r1} - C_r$ | $R_{r1} = -\frac{a_n}{c_n}$, $C_r = -\frac{c_n}{a_n^2}$ |
| $a_n$ (complex)<br>$c_n$ (complex)<br>($a_n = a_r + ja_i$,<br>$c_n = c_r + jc_i$) | $R_c - L_c$ in series with $G_c - C_c$ | $L_c = \frac{1}{2c_r}$<br>$R_c = -2a_r +$<br>$2(a_r c_r + a_i c_i) L_c L_c$<br>$C_c = [a_r^2 + a_i^2 +$<br>$2(a_r c_r + a_i c_i) R_c L_c]^{-1}$<br>$G_c = -2(a_r c_r + a_i c_i) C_c L_c$ |

Equation (6) is linear in terms of its unknowns $c_n$, $d$, $h$, and $\tilde{c}_n$ under assumption of known poles $a_k$. Now a set of starting poles should be chosen as complex conjugate with imaginary parts $\beta$ linearly distributed over the frequency range of interest and substituted in (7). Each pair is chosen as bellow [6]

$$a_n = -\alpha + j\beta\,, a_{n+1} = -\alpha - j\beta \tag{10}$$

Where $\alpha = \beta / 100$.

According to [6], after (6) is solved, to achieve more accurate approximation, the new poles are computed through computing eigenvalues of the following matrix:

$$H = A - b\tilde{c}^T \tag{11}$$

Where $A$ is a diagonal matrix including staring poles, and *b* is column vector of ones. $\tilde{c}$ is a row vector of $\tilde{c}_i$. These new poles are then substituted in (6) and solved once more. This process is continued up to the following mean square error is near to zero using least square technique, that is

$$|\varepsilon| = \sqrt{\sum_{k=1}^{N} (f(s_k) - F(s_k))^2} \to 0 \tag{12}$$

Finally, once the iteration process is finished, equivalent circuit is achieved as shown in Fig. 5. If there is no poles, $R_0, C_0$ are computed as $R_0 = 1/d$ and $C_0 = h$, else all lumped elements in the other branches are extracted based on table 1. Further information in more detail about vector fitting method can be found in [6].

Table 2. All parameters for the two scenarios in this study.

| Parameters / Scenario | L | h | ΔL | $\sigma_u$ | $\varepsilon_{ru}$ | $\sigma_d$ | $\varepsilon_{rd}$ | $\sigma_o$ | $\varepsilon_{ro}$ |
|---|---|---|---|---|---|---|---|---|---|
| **first** | 3m | 1m | 5m | 0.001S/m | 10 | 0.01S/m | 10 | 4S/m | 4 |
| **second** | 3m | 1m | 5m | 0.01S/m | 10 | 0.001S/m | 10 | 4S/m | 4 |

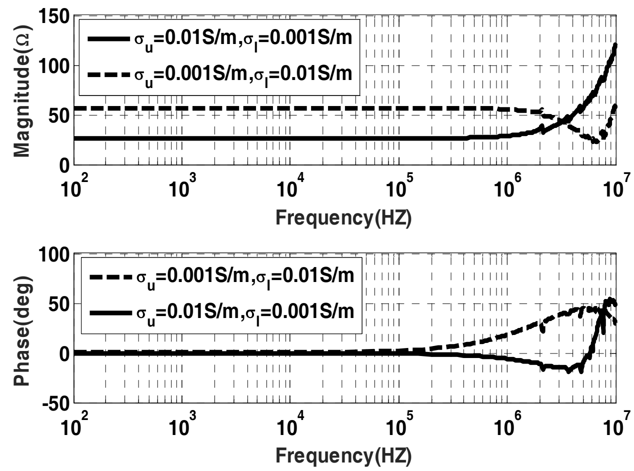



Fig. 6. Computed input impedance of the vertical rod buried in horizontally two-layered soil for two scenarios using FEM.

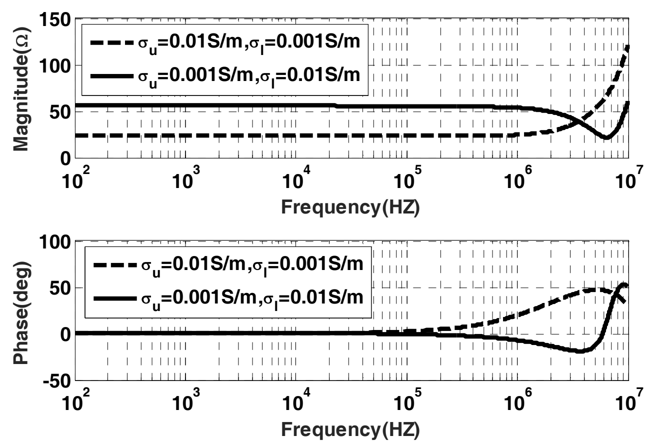



Fig. 7. Computed input impedance of the vertical rod buried in horizontally two-layered soil for two scenarios using VF.

## III. VERTICAL RODS IN THE PRESENCE OF OCEANS

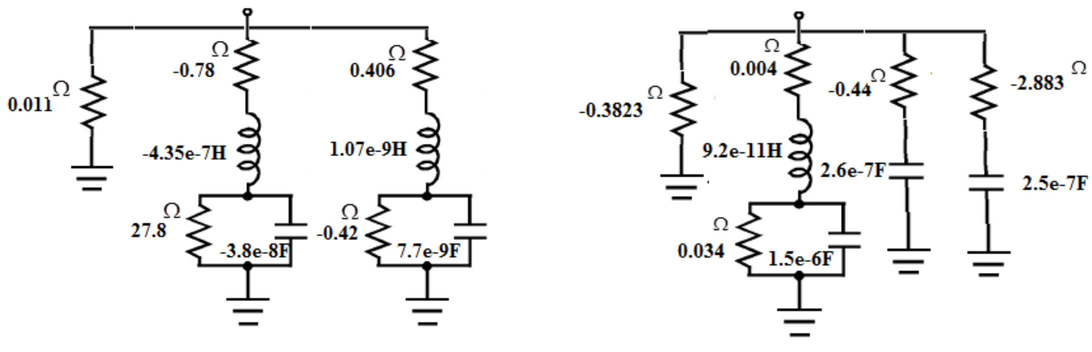
In this section based on the VF theory, equivalent circuit of the vertical rod as shown in Fig. 5 with and without considering ocean is first extracted. Then, this equivalent circuit can be imported to EMTP so that transient voltage of grounding rod is easily computed. This quantity in terms of safety

Table 3. Starting and final poles in vector fitting process for the first scenario.

| **Starting poles** | -383 - 38345i | -383 + 38345i | -383E+5 – 383E+7i | -383E+5+ 383E+7i |
|---|---|---|---|---|
| **Final poles** | -311E+4 + 331E+4i | -311E+4 – 331E+4i | -411E+5 + 985E+5i | -411E+5 – 985E+5i |

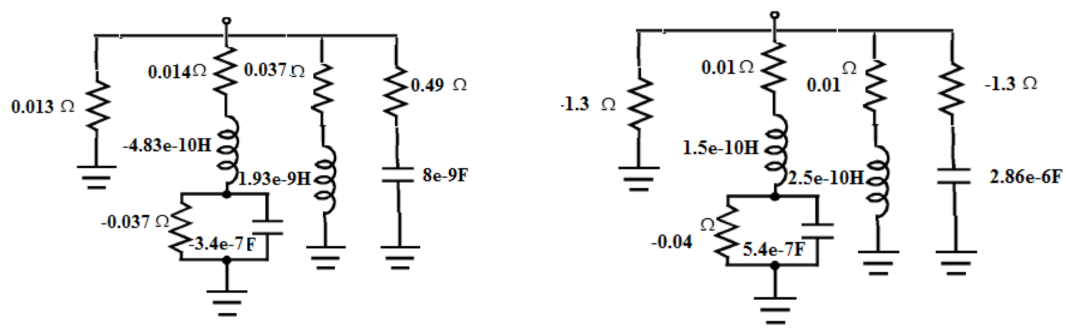
Table 4. Starting and final poles in vector fitting process for second scenario.

| **Starting poles** | -264 - 26407i | -264 + 26407i | -264E+5 – 264E+7i | -264E+5 + 264E+7i |
|---|---|---|---|---|
| **Final poles** | -264179 + 0.0i | -385E+5 + 0.0i | -230E+5 + 893E+5i | -230E+5 – 893E+5i |




(a) (b)

Fig. 8. Equivalent circuit of the rod buried in horizontally two-layered soil for the first scenario using VF, (a) without ocean effect, (b) with ocean effect.




(a) (b)

Fig. 9. Equivalent circuit of the rod buried in horizontally two-layered soil for the second scenario using VF, (a) without ocean effect, (b) with ocean effect.

criteria is of importance.

## *A. Exact Equivalent Circuit*

Fig. 4 shows a vertical rod of length L buried in horizontally two-layered soil with spacing $\Delta L$ from the ocean-land interface. The ocean is represented as a lossy media with electrical parameters $\sigma_o, \varepsilon_{ro}$. To extract equivalent circuit, the frequency response of network which here means

Table 5. All parameters in (13) used in first and subsequent strokes.

| Current \ Parameters | $I_0$(kA) | $\tau_1$($\mu$s) | $\tau_2$($\mu$s) | n |
|---|---|---|---|---|
| **First stroke** | 28 | 1.8 | 95 | 2 |
| **Subsequent stroke** | 10.7 | 0.25 | 2.5 | 2 |
| | 6.5 | 2 | 230 | 2 |

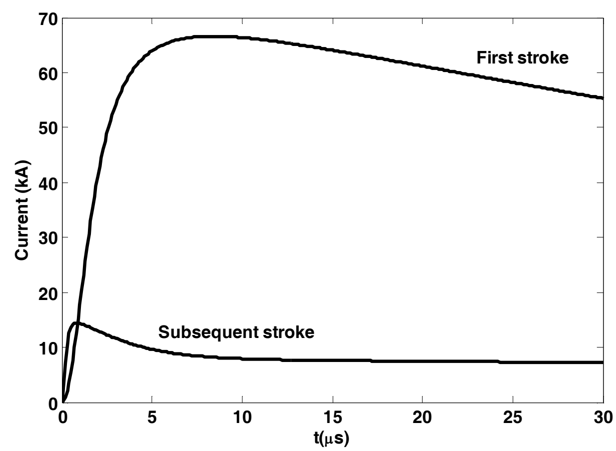



Fig.10. Time-domain representtion of lightning currents namely first and subsequent strokes.

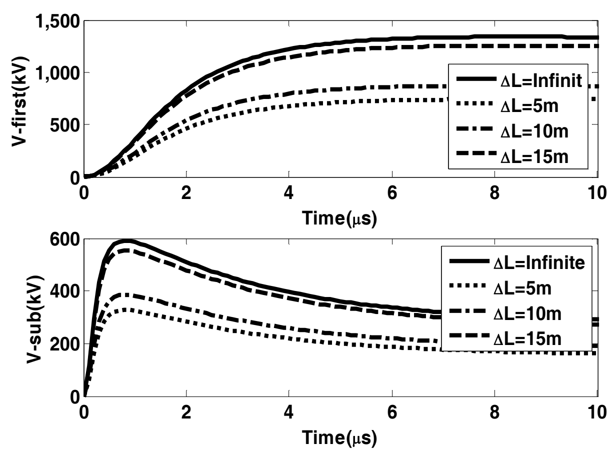



Fig. 11. Grounding potential rise of the vertical rod buried in horizontally two-layered soil ($\sigma_u = 0.01\mathrm{S/m}, \sigma_l = 0.001\mathrm{S/m}$) for different values of $\Delta L$ using EMTP.

the input impedance is first computed by FEM. In this study, two scenarios are investigated. The physical and electrical parameters of different layers for two scenarios are listed in table 2. Fig. 6 shows the input impedance for the two scenarios. The VF method is first started with staring poles,

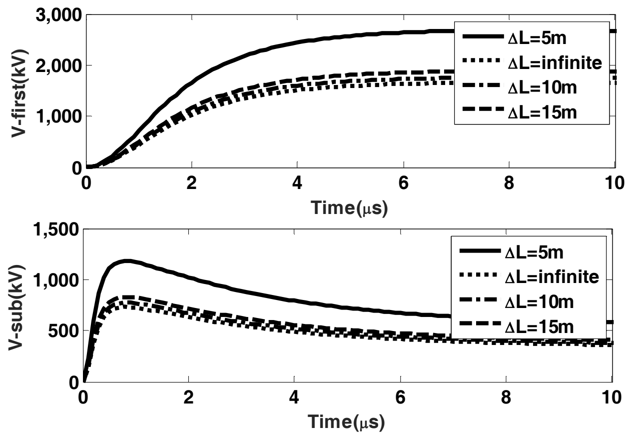



Fig. 12. Grounding potential rise of the vertical rod buried in horizontally two-layered soil in the beighboring an ocean ($\sigma_u = 0.001 S/m, \sigma_l = 0.01 S/m$) for different values of $\Delta L$ using EMTP.

and when the iteration process is finished, the final poles as listed in table 3 and 4 are then extracted. Finally, the approximated input impedances for the two scenarios based on the VF method are shown in Fig. 7. Comparison of Figs. 6 and 7 illustrates the excellent accuracy of the VF method in comparison with FEM. Now using final poles and table 1, the equivalent circuits respectively for the first and second scenarios are shown in Fig. 8 and 9. Comparison of these circuits with and without considering the ocean effect illustrates the considerable difference which obviously influences the lightning performance of power systems such as overhead lines connected to arresters [11-13].

## *B. Transient Analysis*

In this section with use of the extracted equivalent circuit and importing into EMTP, the transient analysis for the two scenarios can be easily carried out. To this end, two typical lightning currents namely first and subsequent strokes as expressed in (13) are used. All parameters in (13) are listed in table 5. Fig. 10 shows the behavior of the two currents in time domain.

$$i(t) = \frac{I_0}{\eta} \frac{(t/\tau_1)^n}{1+(t/\tau_2)^n} e^{(-t/\tau_2)} \quad , \quad \eta = e^{-(\tau_1/\tau_2)(n(\tau_1/\tau_2))^{1/n}} \tag{13}$$

To show the importance of ocean presence, the grounding potential rise (GPR) for different values of $\Delta L$ under first and subsequent strokes can be easily computed by EMTP. Figs. 10 and 11 illustrate GPRs for the first and second scenarios respectively. In these two figures, GPRs are also compared with the individual ones in the absence of the ocean. As seen in these figures, for $\Delta L > 15 m$ the ocean-land mixed propagation path can be disregarded, elsewhere this effect influences the peak value of the GPRs. As known, the effective length of vertical rod is strictly dependent on the GPRs [14].

Therefore this effect in designing grounding rods is of importance as well. Further study in more detail about impact of this effect on the effective length is explained in another study.

## IV. Conclusion

In this study, the effect of ocean-land mixed propagation path on the equivalent circuit and grounding potential rise (GPR) of the grounding rod was investigated. Both equivalent circuit and GPR are affected for $\Delta L < 15\mathrm{m}$. In addition, when the first layer is highly resistive (second scenario), the ocean effect results in increasing GPR, whereas for highly conductive layer (first scenario) the GPR is decreased. These make the ocean-land mixed propagation path important in designing grounding systems.The last key finding is that in the near of oceans, the predicting formulae for effective length and impulse impedance in homogenous soils [15, 16] should be modified. This challenge is of importance that is in progress.

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