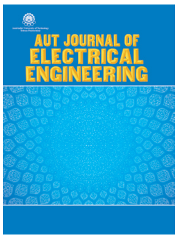

AUT Journal of Electrical Engineering

AUT J. Electr. Eng., 55(1) (2023) 107-114
DOI: 10.22060/eej.2022.21747.5491

# GPR of Multiple Vertical Rods under Lightning Strokes Considering Ionization, Dispersion, and Non-Homogeneity of Lossy Soils

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**ABSTRACT:** In this paper, different aspects of lossy soils including ionization, and dispersion on the Grounding Potential Rise (GPR) of multiple vertical rods under lightning return strokes are simultaneously investigated. In all analyses, an efficient modeling approach called Improved Multiconductor Transmission Line (IMTL) is adopted. In the case of single rod, numerical analyses show that when there are the two mentioned aspects, GPR is decreased further with respect to situations where only one aspect is considered. This reduction is considered more for highly resistive soils, and fast-fronted lightning currents. In the case of multiple rods, however, it is placed between the GPRs of only-ionized and only-dispersive soils. Moreover, sensitivity analysis on the non-homogeneity effect in ionized and dispersive soils is carried out. Finally, comprehensively predicting formulae for GPR of multiple rods versus parameters of lightning current, lossy soil and rod are extracted.

**Review History:**

Received: Sep. 03, 2022
Revised: Nov. 08, 2022
Accepted: Nov. 15, 2022
Available Online: Mar. 01, 2022

**Keywords:**

Ionization
Dispersion
Non-Homogeneity
Multiple Rods
Lightning Stroke
GPR

## 1- Introduction

Multiple vertical rods as typical grounding systems are designed to provide a sufficiently low impedance path, allowing large lightning currents to dissipate into the soil with acceptable low Grounding Potential Rise (GPR). Fig. 1 shows different arrangements of rods, including single, double, triple, and quadruple rods. Such grounding systems are typically used in distribution power system and telecommunication. Proper design of such devices are strictly dependent upon considering ionization [1], dispersion [2] and nonhomogeneity of soil [3]. Ionization occurs when the electric field of soil surrounding the rods is exceeded from its critical value, dispersion takes place in soils with frequencydependent parameters, and nonhomogeneity is justified in multi-layer soils.

There are a number of methods for analysis and design of grounding systems, including the frequency-domain method [4, 5] used for only-dispersive soils, and the time-domain method [6, 7] adopted for only-ionized soils. In cases where soil ionization and dispersion occur simultaneously, the mixed frequency-time domain method [8-11] are preferred. Although all of these method are accurate, they are complex and time consuming.

In contrast to the above –mentioned methods, Guardado et. al [12] proposed a relatively simple and efficient method, known as Multi-Conductor Transmission Line model (MTL), that is accurate enough to deal with dispersive soils [13]. Recently, the proposed method has been improved to treat non-linear phenomenon of soil ionization (IMTL) [14].

To the best of our knowledge, there is no research on the computation of GPR of multiple vertical rods buried in a lossy soil that considers the simultaneous effects of soil ionization and dispersion (both affected soil). It is worth noting that the cases of only-dispersive [4], only-ionized [7], and neitheraffected soils [16] have been treated in the literature. In this paper, we intend to study the case of both affected soil when computing the transient GPR of buried multiple vertical rods and compare the results with those obtained in the case of single-affected soil (only-ionized and only-dispersive soils). In the case of a single rod, we show that the simultaneous use of soil ionization and dispersion in the modeling causes further reduction in the value of GPR as compared to the case where each phenomenon is considered separately. The amount of reduction is further accentuated when treating highly resistive soils and fast-fronted lightning currents. In other words, the grounding performance of a single rod buried in these circumstances is greatly improved. In the case of multiple rods, however, the value of GPR in both ionized and dispersed soil lies between those of the only-ionized and only-dispersive soils. Besides, the sensitivity analysis of the non-homogeneity effect in ionized and dispersive soils provides a comprehensive platform to study the soil

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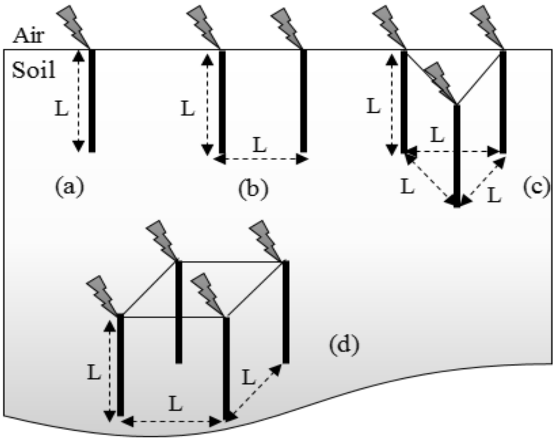


**Fig. 1. Multiple rods under lightning stroke current, (a): single, (b):double, (c): triple, and (c): quadruple rods.**

dependence of the GPR of buried rods. Finally, closed-form expressions are proposed that can accurately predict the value of GPR for a multiple rod buried in a dispersive and ionized lossy soil when subjected to a lightning current waveform.

The manuscript is organized as follows: Section 2 provides the modeling principles of dispersion, ionization and non-homogeneity of a lossy soil. Section 3 is focused on the validity of the MTL/IMTL for predicting the GPR of multiple vertical rods buried in lossy soils in the presence of dispersion and ionization. Section 4 presents a comprehensive sensitivity analysis that determines how the GPR of a multiple rod buried on a lossy soil is affected based on changes in various soil characteristics, including dispersion, ionization and non-homogeneity. In Section 5, the derivation of closed-form expressions is described for calculation of GPR of a multiple rod buried in a dispersive and ionized lossy soil when subjected to a lightning current waveform.

## 2- DIFFERENT CHARACTERISTICS OF SOIL

In the analyses carried out in this study, we consider four characteristics of soil. The first characteristic is dispersion which is demonstrated as a lossy half-space with frequency-dependent resistivity and permittivity [18] as below:

$$\rho(f)=\rho_0\left(1+h\left(\rho_0\right)\times\left(f/MHz\right)^{\gamma}\right)^{-1} \tag{1}$$

$$\varepsilon_r(f)=\varepsilon'_{r\infty}+\frac{\tan\left(\pi\gamma/2\right)\times10^{-3}\times h\left(\rho_0\right)\times\left(f/1MHz\right)^{\gamma}}{\left(2\pi\varepsilon_0\rho_0\right)} \tag{2}$$

where γ = 0.54, ε’ r∞ = 12 and. h(ρ0) = 1.26 ρ0 0.73 .This characteristic is more observed in highly resistive soils and fast-fronted currents [2].

The second characteristic of soil is ionization which is a nonlinear phenomenon and occurs under high-valued lightning currents so that the induced electric field inside the soil becomes greater than its critical electric field value at which impact ionization phenomena and hence breakdown occurs. In such soils, the critical electric field is computed as below:

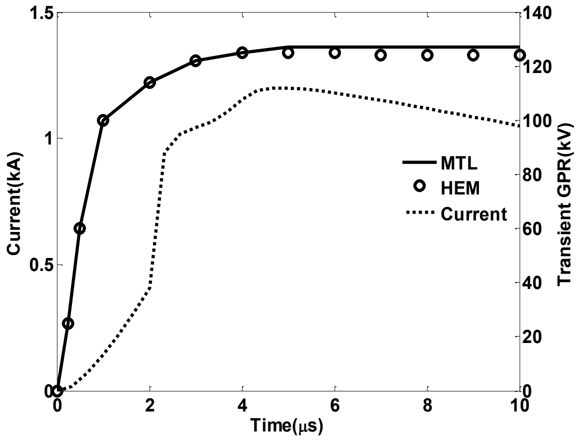


**Fig. 2. Typical lightning current in the first example as well as transient GPR of triple rods based on the MTL and HEM [26].**

$$E_c=241\rho^{0.215} \tag{3}$$

where Ec is critical electric field (in kV/m), and ρ is resistivity (in Ω.m) of the lossy soil [19].

The third characteristic of soil, which occurs in both-affected soil, is the same as only-ionized soil except that the soil electrical parameters are computed from (1) and (2).

Finally, the fourth characteristic of soil is non-homogeneity, which takes place in both-affected soils (all-affected soil). In this study, a horizontally two-layered soil is considered as a heterogeneous soil. The analysis in such soils is the same as both-affected soil except that the apparent low-frequency resistivity [17] should be used in (1), that is:

$$\rho_{0a}=\begin{cases}\rho_{0u}/\{1+\left[\left(\rho_{0u}/\rho_{01}\right)-1\right]\left[1-e^{1/k\left(d+2t\right)}\right]\}\rho_{0u}>\rho_{01}\\ \rho_{0u}/\{1+\left[\left(\rho_{01}/\rho_{0u}\right)-1\right]\left[1-e^{1/k\left(d+2t\right)}\right]\}\rho_{0u}<\rho_{01}\end{cases} \tag{4}$$

where $\rho_{0u}$ and $\rho_{01}$ are respectively low-frequency resistivity of the upper and lower layers. Also, d and t are the burial depth and thickness of the upper layer, respectively. In addition, k is the reflection factor defined as $k=(\rho_{0u}-\rho_{01})/(\rho_{0u}+\rho_{01})$. In this case, the two-layer soil is first approximated with a single-layer dispersive soil with low-frequency resistivity ρ0 = ρ0a , and then Eqs. (1) and (2) are adopted to express the frequency variations of resistivity and permittivity in the two-layer dispersive soil.

## 3- VALIDITY

The validity of the MTL and IMTL methods for computing the transient GPR of buried single vertical and horizontal electrodes has already been demonstrated [20-25]. To expand their validity for predicting the transient GPR of multiple rods buried in a ionized and dispersive soil, we adopt a combined approach, called Hybrid Electromagnetic (HEM), that uses the measurement and full-wave methods [26].

In the first example, an arrangement (Fig. 1(c)) composed of three vertical rods (triple rods) with L = 3m length and separation of 1m, buried in an only-dispersive soil with ρ0 = 1000Ωm is considered [26]. The arrangement is injected by a double-peak current, as shown in Fig. 2. A good agreement

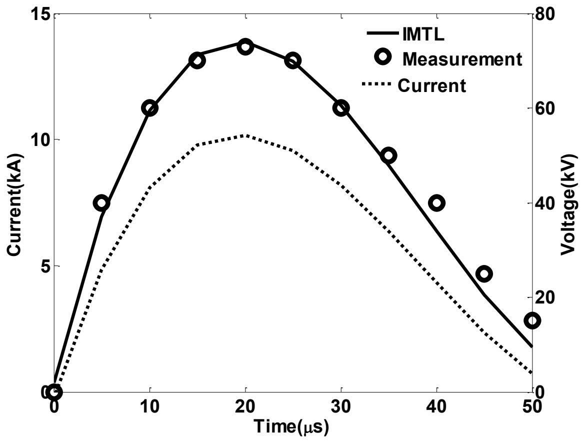


**Fig. 3. Typical lightning current in the second example as well as transient GPR of quadruple rods based on the MTL and measurement [27].**

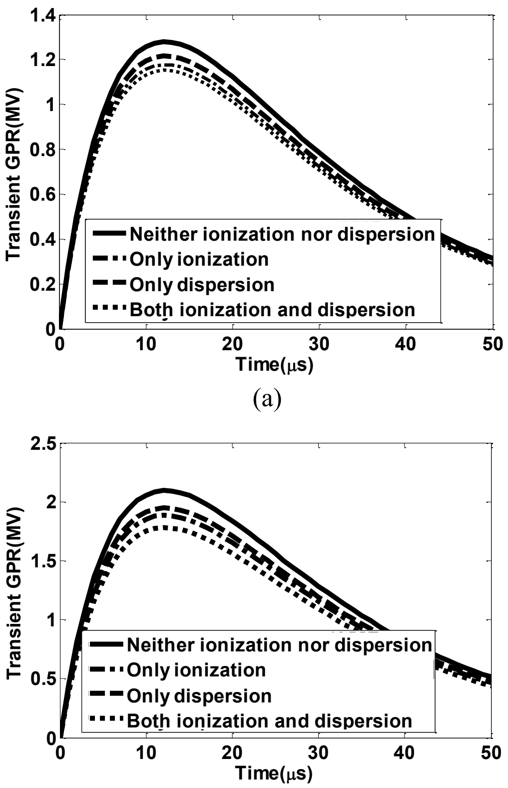
between the two transient GPRs based on the MTL and HEM [26] is observed.

In the second example, a four-driven rods (quadruple rods) is buried in an only-ionized soil with resistivity ρ = 63Ωm and critical electric field Ec = 500kV/m [27]. In this arrangement (Fig. 1(d)), each rod has a length of L = 3.05m and radius of a = 12.7mm while the separation length among rods is D = 3.09m (D ≈ L). The rods is injected by a slow-fronted current as shown in Fig. 3. The transient GPR based on the IMTL and measurement [27] is included in the same figure. A study of the results in Fig. 3 demonstrates the validity of the IMTL method.

The arrangement of quadruple rods is injected by a slow-fronted current as shown in Fig. 3. The transient GPR based on the IMTL and measurement [27] is included in the same figure as well. From this figure, good agreement is achieved.

## 4- GPR OF MULTIPLE RODS

In this section, the MTL/IMTL approach is first applied to single vertical rods buried in a lossy soil, considering four scenarios, namely, neither dispersion nor ionization, only ionization, only dispersion, and both dispersion and ionization. The significance of ionization and dispersion on the transient GPR of multiple rods is investigated separately and simultaneously. The injected currents are slow-fronted (8/20μs – 50kA) and fast-fronted (1/20μs – 20kA) currents, *i.e*, the first and subsequent stroke currents. The current waveform is defined based on a double-exponential function. The vertical rod is of length 3m, radius 12.5 mm inside a lossy soil with resistivity of ρ = 100,1000Ωm . Simulation results based on the MTL/IMTL method for four scenarios under the first stroke current are shown in Fig. 4. From this figure, it can be deduced that for poorly resistive soils (ρ = 100Ωm), the effect of dispersion is low enough so that the only ionized and both-affected soils have the same behaviors. For highly resistive soils however (ρ = 1000Ωm), on the other hand, this effect is more discernable. Moreover, the simultaneous occurrence of soil ionization and dispersion causes further reduction in the value of GPR as compared to the case where each one is takes place separately, especially in highly resistive soils. It follows that in both-affected soils, the grounding performance is improved as compared to the cases of only-ionized and only-dispersive soils.



(a)

(b)

**Fig. 4. Transient GPR of single rod in different soils, with (a): $\rho_0$ = 100 Ωm, and (b): $\rho_0$ = 1000 Ωm .**

Now, the effect of multiple rods on the transient GPR is investigated. The arrangements include single, double, triple and quadruple rods, where the length of each rod and the separation distance among rods are 3m. Simulation are performed for different arrangements and two values of resistivity $\rho_0$ = 100 Ωm and 1000 Ωm when subjected to the first stroke current. The results for the double, triple and quadruple rods are shown in Figs. 5, 6, and 7, respectively. From these figures, the following findings can be inferred.

For multiple rods, the injected current to each rod is less than the one in single vertical rod since the injected lightning current is equally divided among rods. Therefore, it is expected that the occurrence of ionization is less probable in multiple rods than in single rod. This is more pronounced in highly resistive soils since the critical electric field is considerably increased (see Eq. (3)), and accordingly, the chance of having ionization in the soil is further reduced. These facts lead to moving the transient GPR in only-ionized soils upward so that it is approaching the individual one in a neither-affected soil.

For multiple rods, the transient GPR in only-dispersive soil also decreases due to the reduced value of the injection current, particularly in highly resistive soils. In fact, the transient GPR is moving downward so that it is the least value

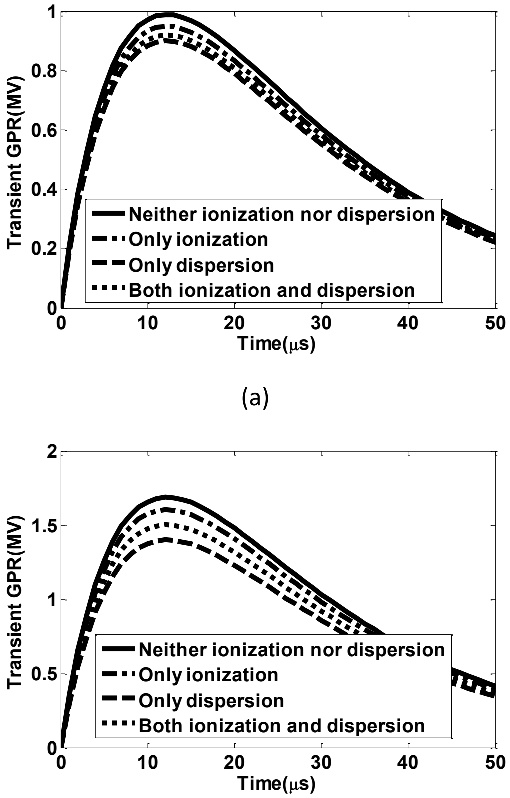


**Fig. 5. Transient GPR of double rods in different soils, with (a): $\rho_0$ = 100 Ωm, and (b): $\rho_0$ = 1000 Ωm**

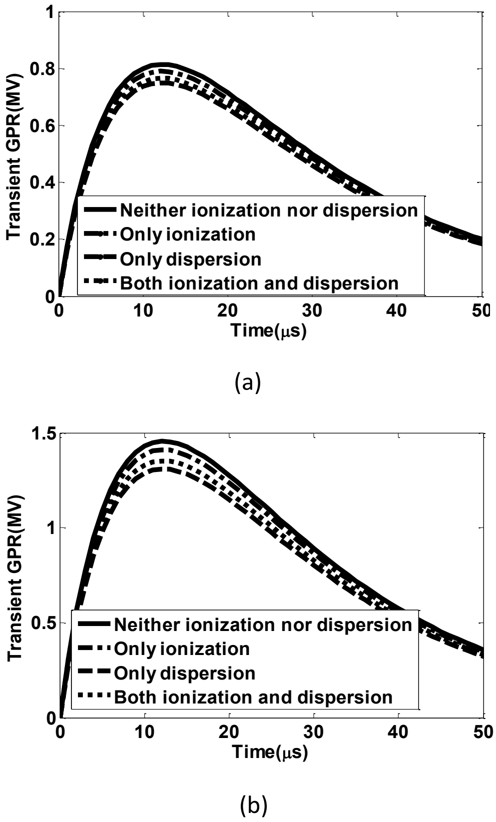


**Fig. 6. Transient GPR of triple rods in different soils, with (a): $\rho_0$ = 100 Ωm, and (b): $\rho_0$ = 1000 Ωm**

**Table 1. GPR (MV) of single rod in different aspects.**

| Current | First stroke | | Subsequent Stroke | |
|---|---|---|---|---|
| $\rho_0$(Ωm) | 100 | 1000 | 100 | 1000 |
| Neither | 1.28 | 2.1 | 0.75 | 1.3 |
| Dispersion | 1.2 | 1.93 | 0.68 | 1.21 |
| Ionization | 1.17 | 1.87 | 0.67 | 1.15 |
| Both | 1.15 | 1.77 | 0.64 | 1.1 |

**Table 2. GPR (MV) of double rods in different aspects of lossy soil.**

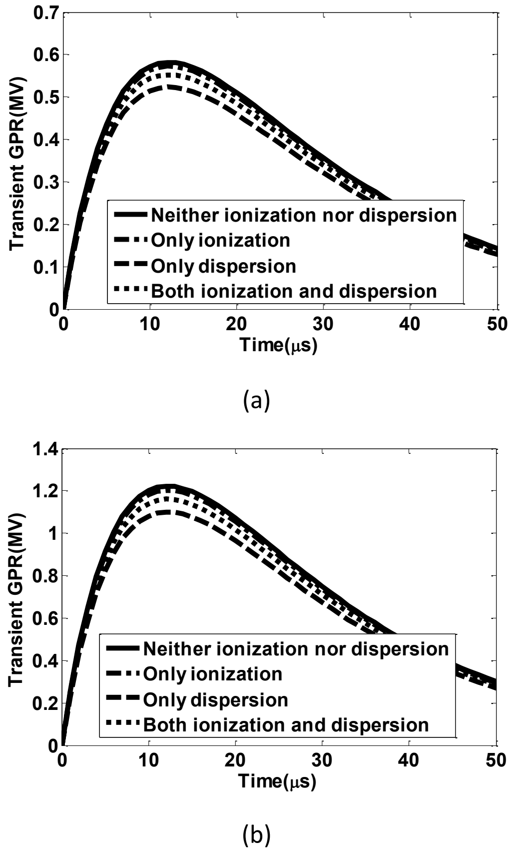
| Current | First stroke | | Subsequent Stroke | |
|---|---|---|---|---|
| $\rho_0$(Ωm) | 100 | 1000 | 100 | 1000 |
| Neither | 1 | 1.7 | 0.62 | 1.02 |
| Dispersion | 0.9 | 1.4 | 0.55 | 0.88 |
| Ionization | 0.95 | 1.6 | 0.58 | 0.97 |
| Both | 0.91 | 1.5 | 0.57 | 0.94 |

**Table 3. GPR (MV) of triple rods in different situations of lossy soil.**

| Current | First stroke | | Subsequent Stroke | |
|---|---|---|---|---|
| $\rho_0$(Ωm) | 100 | 1000 | 100 | 1000 |
| Neither | 0.82 | 1.46 | 0.50 | 0.77 |
| Dispersion | 0.74 | 1.30 | 0.45 | 0.67 |
| Ionization | 0.79 | 1.41 | 0.48 | 0.75 |
| Both | 0.76 | 1.35 | 0.46 | 0.72 |

**Table 4. GPR (MV) of quadruple rods in different aspects of lossy soil.**

| Current | First stroke | | Subsequent Stroke | |
|---|---|---|---|---|
| $\rho_0$(Ωm) | 100 | 1000 | 100 | 1000 |
| Neither | 0.58 | 1.22 | 0.5 | 0.62 |
| Dispersion | 0.52 | 1.1 | 0.455 | 0.55 |
| Ionization | 0.57 | 1.2 | 0.485 | 0.61 |
| Both | 0.55 | 1.16 | 0.465 | 0.59 |



(a)

(b)

**Fig. 7. Transient GPR of quadruple rods in different soils, with (a): $\rho_0 = 100\ \Omega$m, and (b): $\rho_0 = 1000\ \Omega$m**

among the other scenarios for multiple rods.

Based on the above findings, it is expected that the transient GPR in both-affected soil will have a middle value between the two cases of only-ionized and only-dispersive soils, as shown in Figs. 5-7. In the case of subsequent stroke current, the reduction in the GPR of multiple rods in each scenario is more discernable due to higher frequency components in the current waveform, as shown in Tables 1-4.

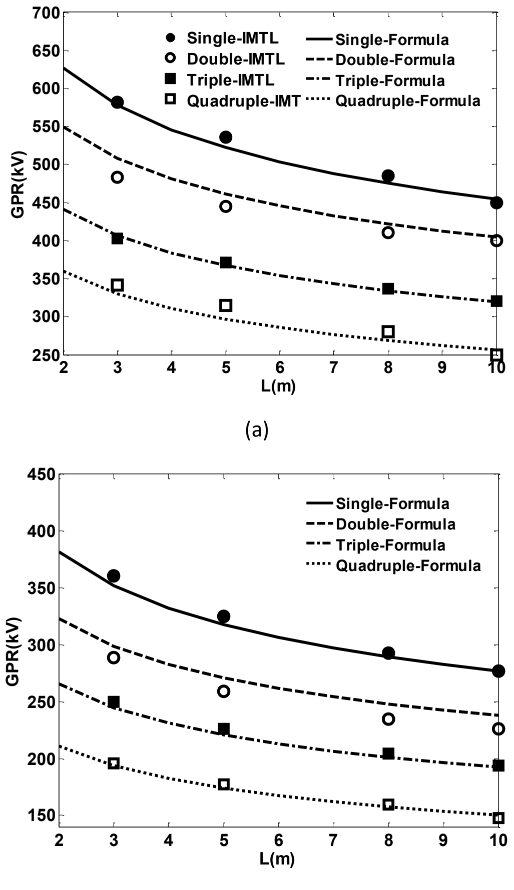
The above findings emphasizes the significance of considering ionized and dispersive soils in the prediction of GPR of multiple rods. It is worth noting that the soil plays an important role in absorbing energy dissipated by the lightning arresters connected to overhead lines [28], which should be considered by power engineers.

## 5- CLOSED-FORM FOR GPR

In lightning-protection engineering applications, the estimation of GPR is of importance since its measurement is not feasible at high frequencies.

### 5- 1- Both-Affected Soils

In line with the previous closed-form expressions proposed for GPR in single-affected soils [15, 16], an estimation of GPR of multiple rods in both-affected soils is proposed. To this aim, the general form as Eq. (5) for each arrangement is first proposed.



(a)

(b)

**Fig. 8. Validity of the extracted formulae versus the rod length for (a): first and (b): subsequent stroke currents with $\rho_0 = 500\ \Omega$m.**

$$GPR = A\frac{\rho_0^x T_M^y I_M^z}{L^P} \tag{12}$$

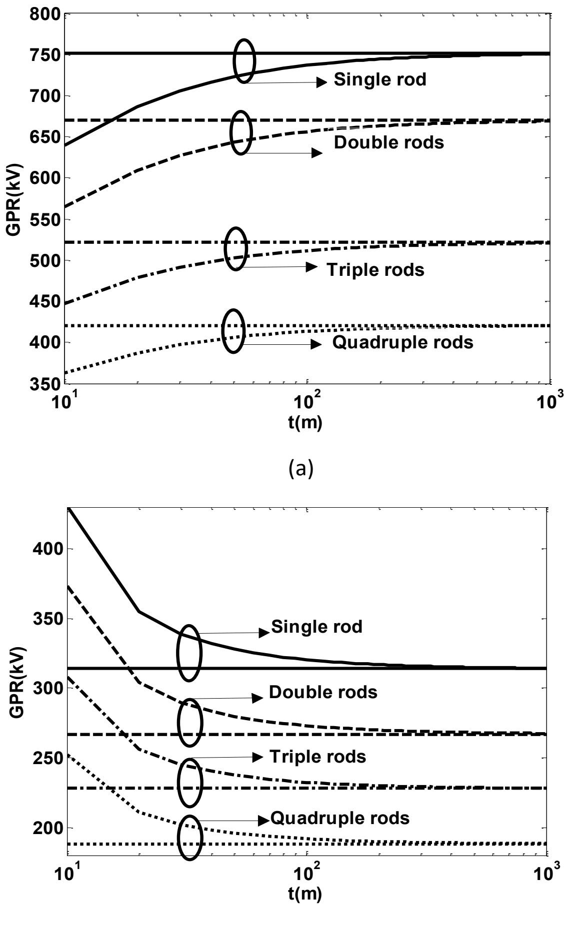
where A, x, y, z and p are the unknown parameters and computed, using an efficient optimization technique called Intelligent Water Drop (IWD) [29-31] for minimizing the following cost functions,

$$|\varepsilon| = \sqrt{\sum_{i=1}^{N}\left|GPR_i^{IMTL} - GPR_i^{formula}\right|^2} \to 0 \tag{13}$$

where N is the number of input-output samples, and $GPR^{IMTL}$ and $GPR^{formula}$ denote the values of GPR computed using the IMTL method and the proposed expression in (5), respectively.

Adopting the above procedure, the following expressions are derived for the GPR of single ($GPR^S$), double ($GPR^D$), triple ($GPR^T$), and quadruple ($GPR^Q$) rods in both-affected soils.

Variations of GPR of single, double, triple, and quadruple rods versus rod length for typical first and subsequent lightning currents are depicted in Fig. 8. A study of the results in this figure clearly demonstrates the validity of the proposed expressions for calculation of single and multiple rods.



(a)

(b)

**Fig. 9. Comparison of GPR of multiple rods in all and both-affected soils versus the upper layer thickness for the (a): first and (b): second scenarios.**

$$GPR^S = 33.85\frac{\rho_0^{0.38}T_M^{0.087}I_M^{0.2}}{L^{0.2}} \tag{14}$$

$$GPR^D = 25.5\frac{\rho_0^{0.4}T_M^{0.1}I_M^{0.213}}{L^{0.19}} \tag{15}$$

$$GPR^T = 25.85\frac{\rho_0^{0.36}T_M^{0.1}I_M^{0.2}}{L^{0.2}} \tag{16}$$

$$GPR^Q = 22\frac{\rho_0^{0.35}T_M^{0.1}I_M^{0.213}}{L^{0.21}} \tag{17}$$

### 5- 2- All-Affected Soils

As defined in Section 1, all-affected soil is a horizontally two-layered media in which ionization and dispersion occur simultaneously. In such soils, the GPR of multiple rods can be computed using Eqs. (7)-(10), except that the apparent resistivity in (4) should be used instead of $\rho_0$. This approximation has been recently used for the transient analysis of the grounding systems [9-11].

Now, a sensitivity analysis on the value of GPR versus the thickness of the upper layer of a horizontally two-layered soils for two scenarios is carried out and shown in Fig. 9. In the first scenario, the low-frequency values of resistivity associated with the upper and lower layers are, respectively, $\rho_{0u}$=1000Ωm and $\rho_{01}$=100Ωm, whereas in the second scenario, the respective values are ρ0u = 100Ωm and ρ01 = 1000Ωm. Referring to Fig. 9, the straight lines are related to both-affected soil, while the others correspond to all-affected soil. From the results in this figure, it can be deduced that when the upper layer thickness, t, is greater than 40m, the GPRs of both- and all-affected soils in both scenarios are virtually the same (with the relative error less than 5%). In addition, for each arrangement of multiple rods in the first scenario, the GPR in all-affected soil is less than the individual one in both-affected soil, whereas they are reversed in the second scenario.

## 6- CONCLUSION

With the aid of an efficient modeling method called MTL/IMTL, the significance of ionization and dispersion on the GPR of multiple vertical rods has been investigated. According to the simulation results, the following key findings are reported.

- When both ionization and dispersion occur in a soil (both-affected soil), the GPR of a single rod is generally decreased, especially for highly resistive soils and fast-fronted currents. This leads to further reduction in the value of GPR as compared to the case where each phenomenon is takes place separately.

- In the case of multiple rods, however, the value of GPR in both ionized and dispersed soil lies between those of the only-ionized and only-dispersive soils. In fact, the GPRs in only-ionized and only-dispersive soils are respectively considered as lower and upper bonds for both-affected soil.

- In the case of non-homogeneous soils, when the upper layer thickness is greater than 40m, the effect of the second layer can be virtually ignored. Also, when the upper layer is denser, the GPR in nonhomogeneous soil is greater than the individual one in homogeneous soil and vice versa.

- Finally, closed-form expressions have been proposed that can accurately predict the value of GPR for both single and multiple rods buried in a dispersive and ionized lossy soil when subjected to a lightning current waveform.

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**HOW TO CITE THIS ARTICLE**

*S. R. Ostadzadeh, S. S. Sajjadi, S. H. H. Sadeghi, GPR of Multiple Vertical Rods under Lightning Strokes Considering Ionization, Dispersion, and Non-Homogeneity of Lossy Soils, AUT J Electr Eng, 55(1) (2023) 107-114.*

**DOI:** 10.22060/eej.2022.21747.5491