

IT308 - Tópicos em Técnicas de Alta Tensão II

Aterramento no Sistema Elétrico Aula-02

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- [Skype: andersonjusto3](skype:andersonjusto3)

Tópicos

- Modelos/Métodos numéricos;
- Impedância Impulsiva;
- Comprimento Efetivo;
- Variação dos parâmetros do solo com a frequência;
- Estratificação do solo;

Modelos/Métodos numéricos

- Existem diversos modelos para computar a impedância dos eletrodos de aterramento na literatura, das quais são baseados em:
 - ❖ Modelos a parâmetros distribuídos (Linha de transmissão-Aula1);
 - ❖ Modelos a parâmetros concentrados (Aula-3);
 - ❖ Métodos numéricos empregados na resolução das equações de Maxwell:
Tais como Método dos Momentos, Método dos Elementos Finitos (MEF) e Partial Element Equivalent Circuit (PEEC).

A Review of Methods for Grounding Grid Analysis

Petar Sarajčev, Slavko Vujević

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Vantagens dos Métodos Numéricos

- Estudar topologias complexas de aterramento;
- Inclusão do efeito da freq. nos parâmetros
- do solo;
- Incluir a estratificação dos solos;
- Mapeamento do campo EM em quanto ponto.



Figure 3 Reinforcement of a wind turbine with foundation earth electrode

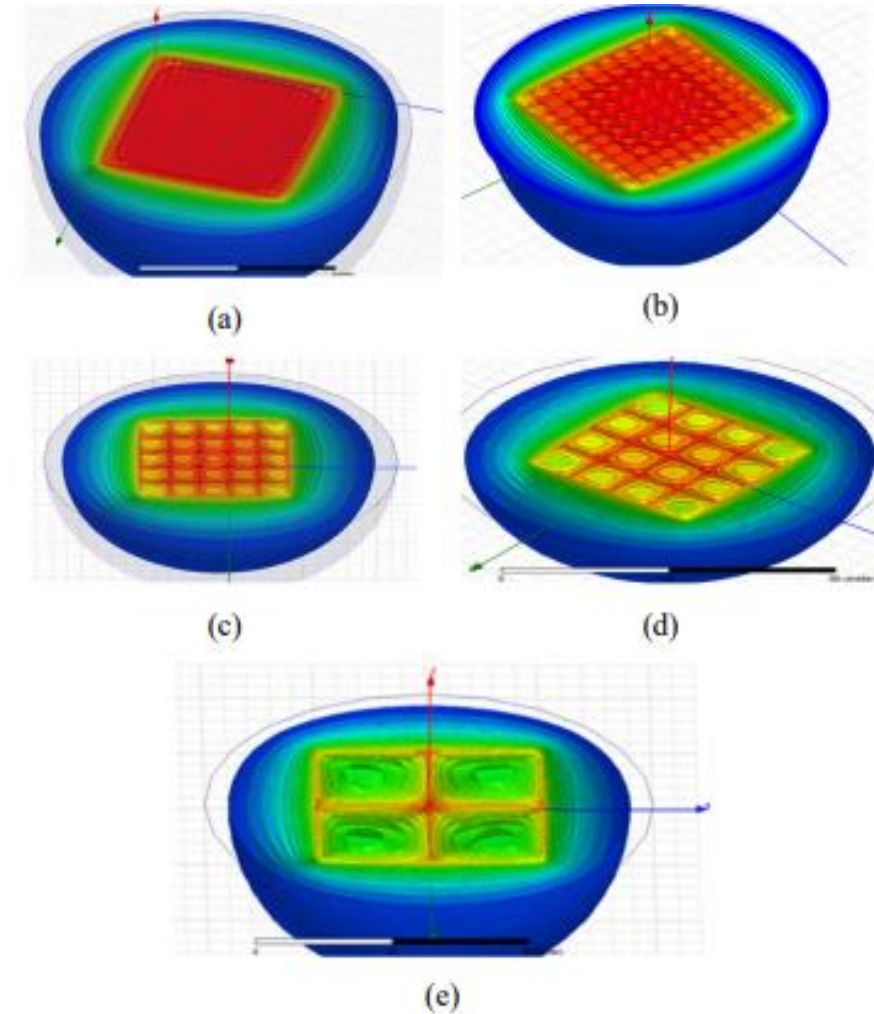


Figure 5. Earth potential for ground meshes, with spacing of (a) 2.5m x 2.5m, (b) 5m x 5m, (c) 10m x 10m, (d) 12m x 12m and (e) 25m x 25m.

Full-wave solver (FEKO)



- O FEKO é um software de simulação eletromagnética para análise de campos eletromagnéticos em estruturas 3D, oferecendo diversos métodos numéricos para a solução das Equações de Maxwell (MOM, FDTD).
- Os eletrodos são desenhados no CADFEKO, onde delimita-se a geometria do problema, os materiais que constituem o objeto e suas grandezas físicas (permeabilidade, permissividade e condutividade elétrica)
- Escolhe-se o tipo de excitação (fonte de tensão) aplicado no ponto de interesse da estrutura. Define-se o tamanho da malha (mesh), e intervalo de frequência a ser analisado.

3D View Search (Alt+S) ...

Home Construct Transform Source/Load Request Mesh Solve/Run Tools View Display options

New Open model Save Import Export 3D view Schematic Notes Model unit Model extents Create mesh CEM validate Script editor Application macro Record macro Cables Windscreen FEKO solver POSTFEKO EDITFEKO Antenna Magus FEKO terminal Parallel Farm out Remote

File Create view Model attributes Meshing Scripting Extensions Run/launch

Configurations 3D view 1

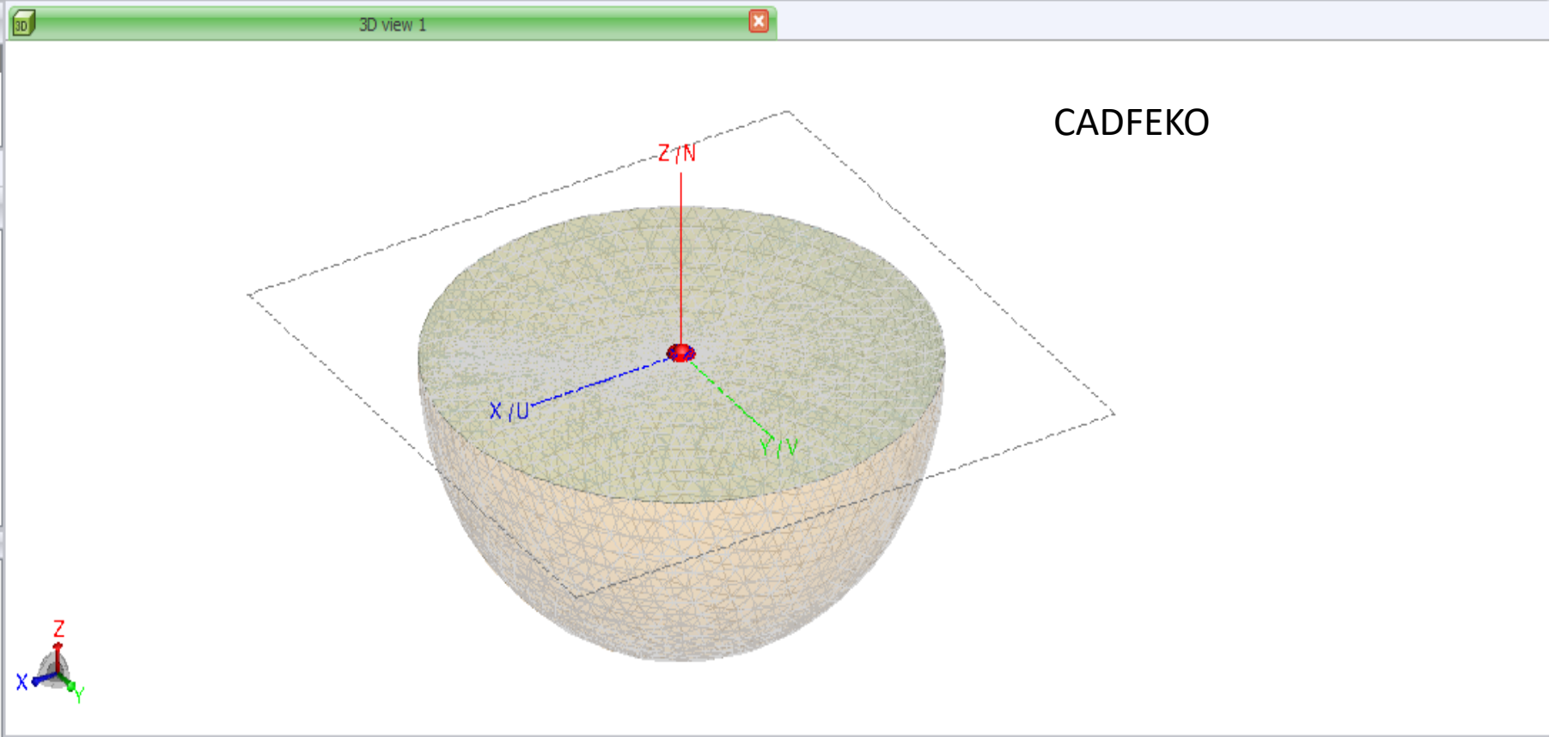
StandardConfiguration1

Construction Configuration

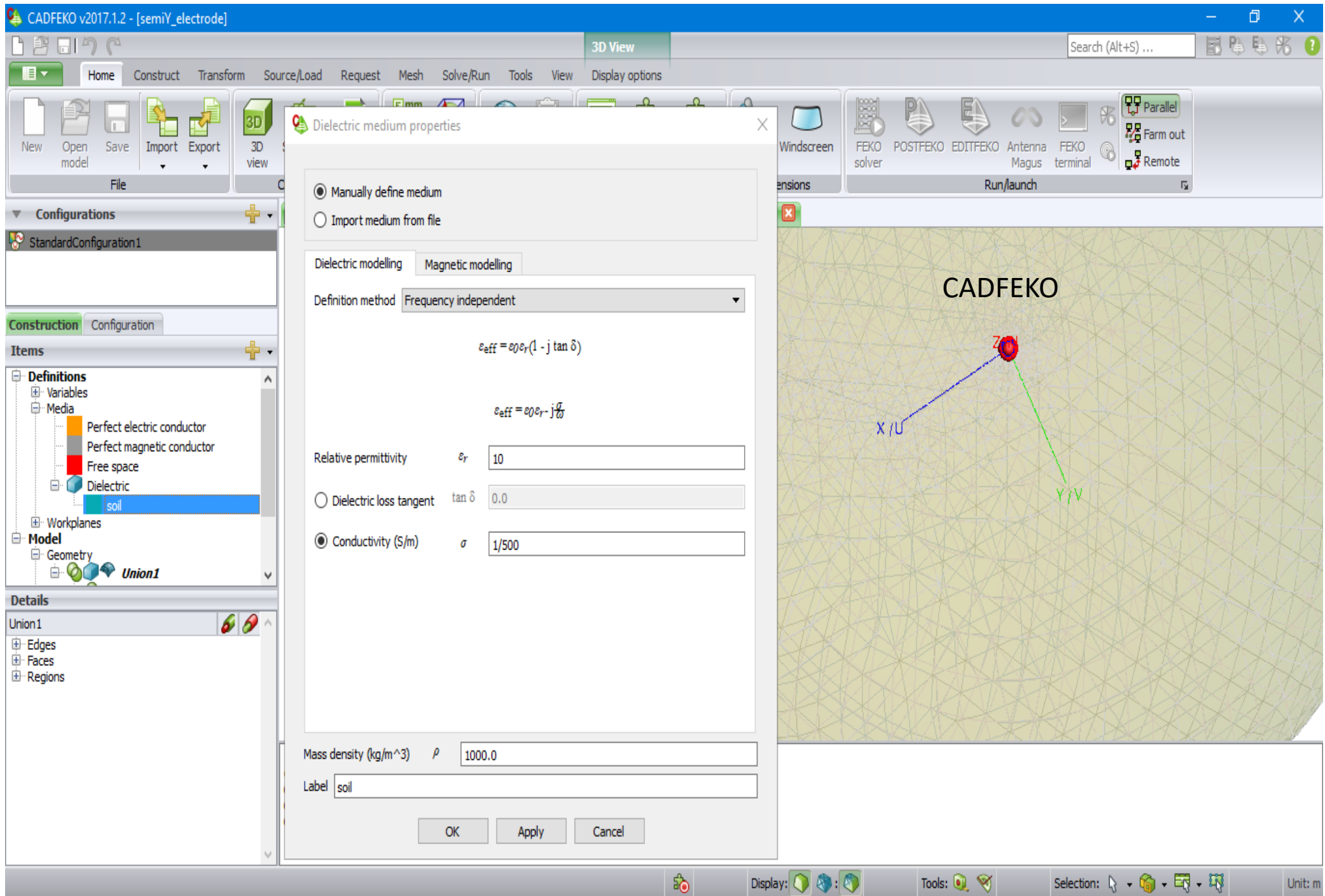
Items

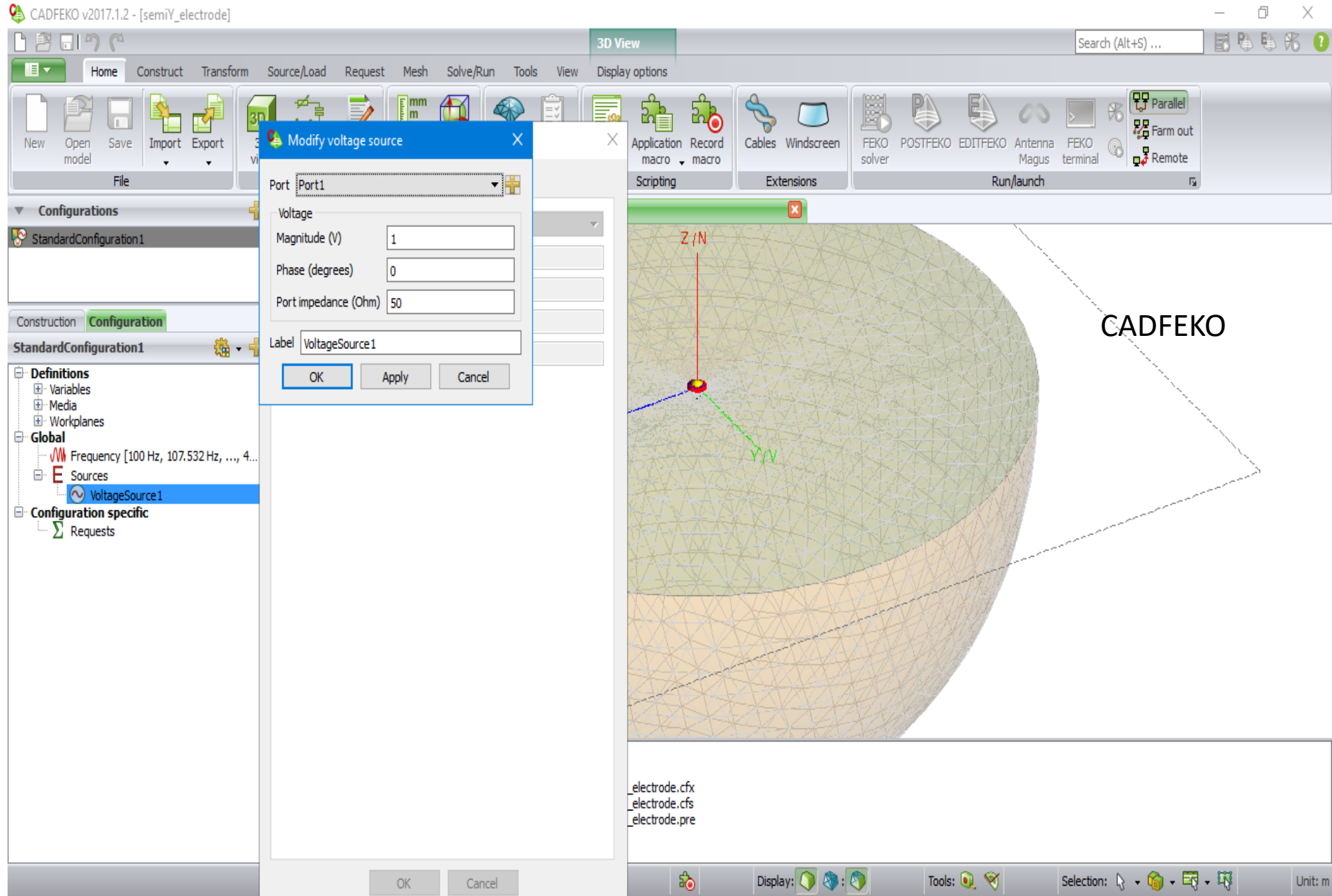
- Definitions
 - Variables
 - Media
 - Workplanes
- Model
 - Geometry
 - Union1
 - Ports

Details



Opening project file...
C:\Users\ander\AppData\Roaming\Skype\My Skype Received Files\semiY_electrode.cfx
C:\Users\ander\AppData\Roaming\Skype\My Skype Received Files\semiY_electrode.cfs
C:\Users\ander\AppData\Roaming\Skype\My Skype Received Files\semiY_electrode.pre



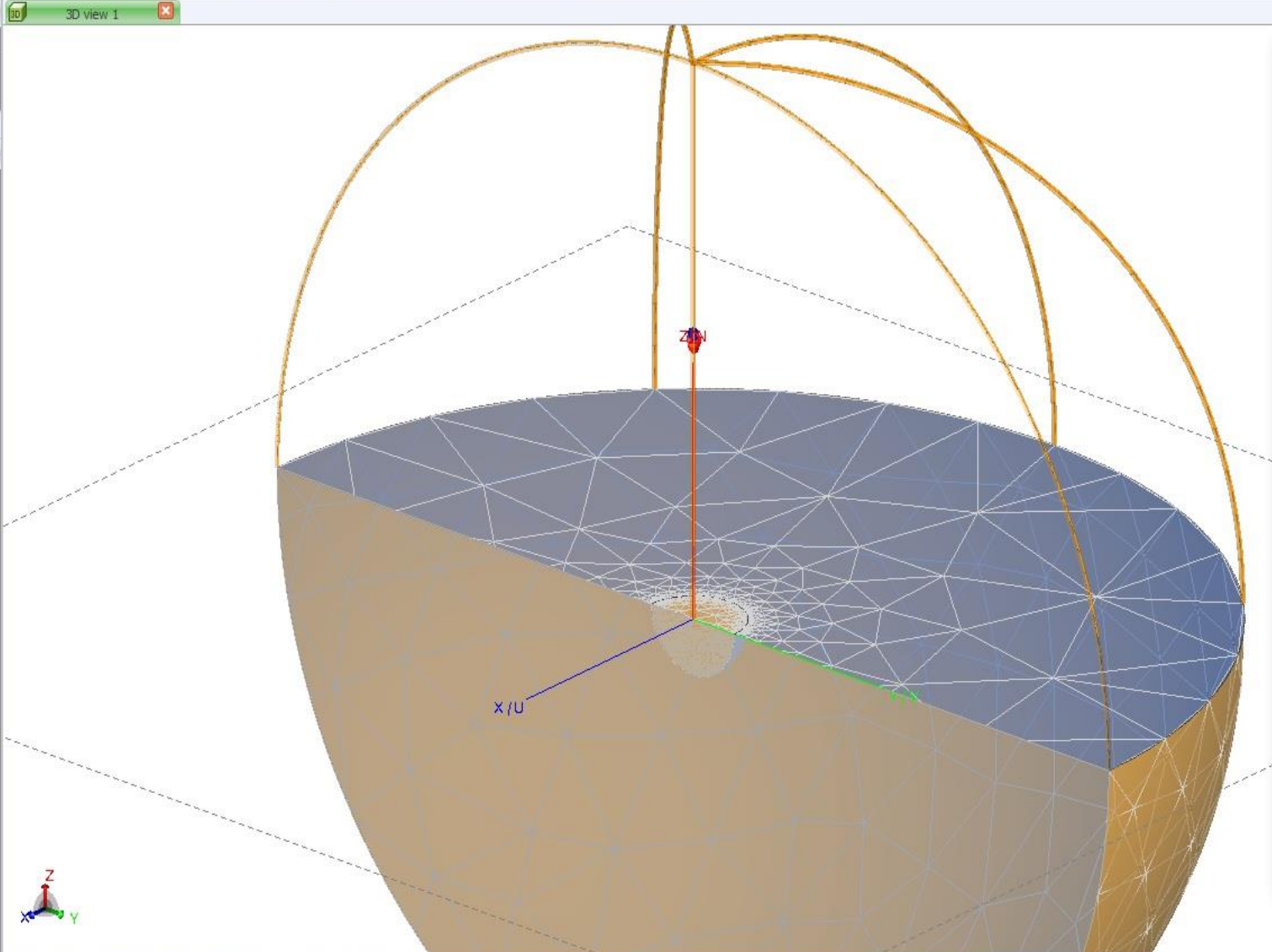




Configurations
StandardConfiguration1

Construction Configuration
StandardConfiguration1

- Definitions
 - Variables
 - Media
 - Perfect electric conductor
 - Perfect magnetic conductor
 - Free space
 - Dielectric
 - soil
 - Workplanes
 - Global
 - Frequency [100 Hz, 150 Hz, ..., 950 Hz, 1...]
 - Sources
 - VoltageSource1
 - Configuration specific
 - Requests



Solution frequency

Frequency Export Advanced

Linearly spaced discrete points

Start frequency (Hz) 100

End frequency (Hz) 1e3

Number of frequencies 19

Frequency increment 50 Hz

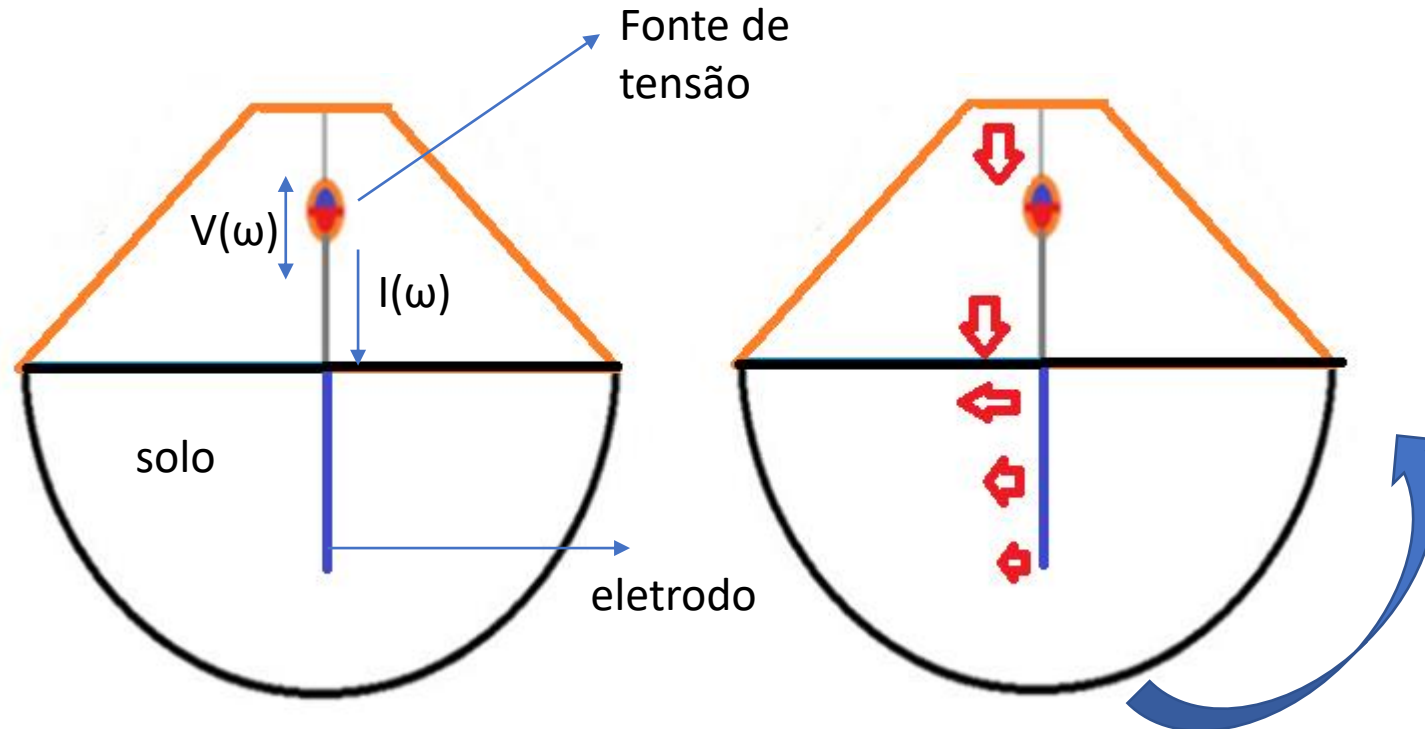
OK Cancel

C:\Users\Anderson\AppData\Local\Temp\Temp1_hemisphere_Martin (2).zip\hemisphere.cfs
C:\Users\Anderson\AppData\Local\Temp\Temp1_hemisphere_Martin (2).zip\hemisphere.pre

Modify cutplane...

solução: Cone/Arco Metálico metálico na borda da semiesfera

$$Z(\omega) = \frac{V(\omega)}{I(\omega)}$$



Domínio Metálico para fechar o caminho da corrente

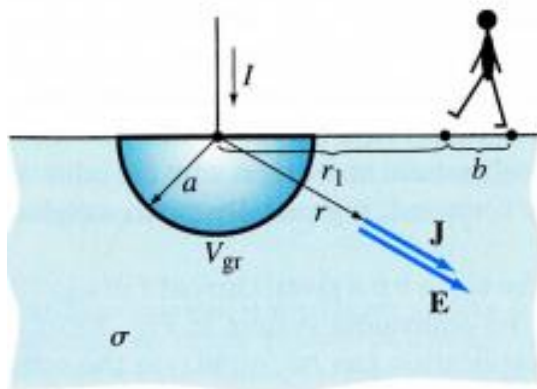
Distribuição da corrente

A seguir são apresentados os resultados para um eletrodo semiesférico

Exemplos



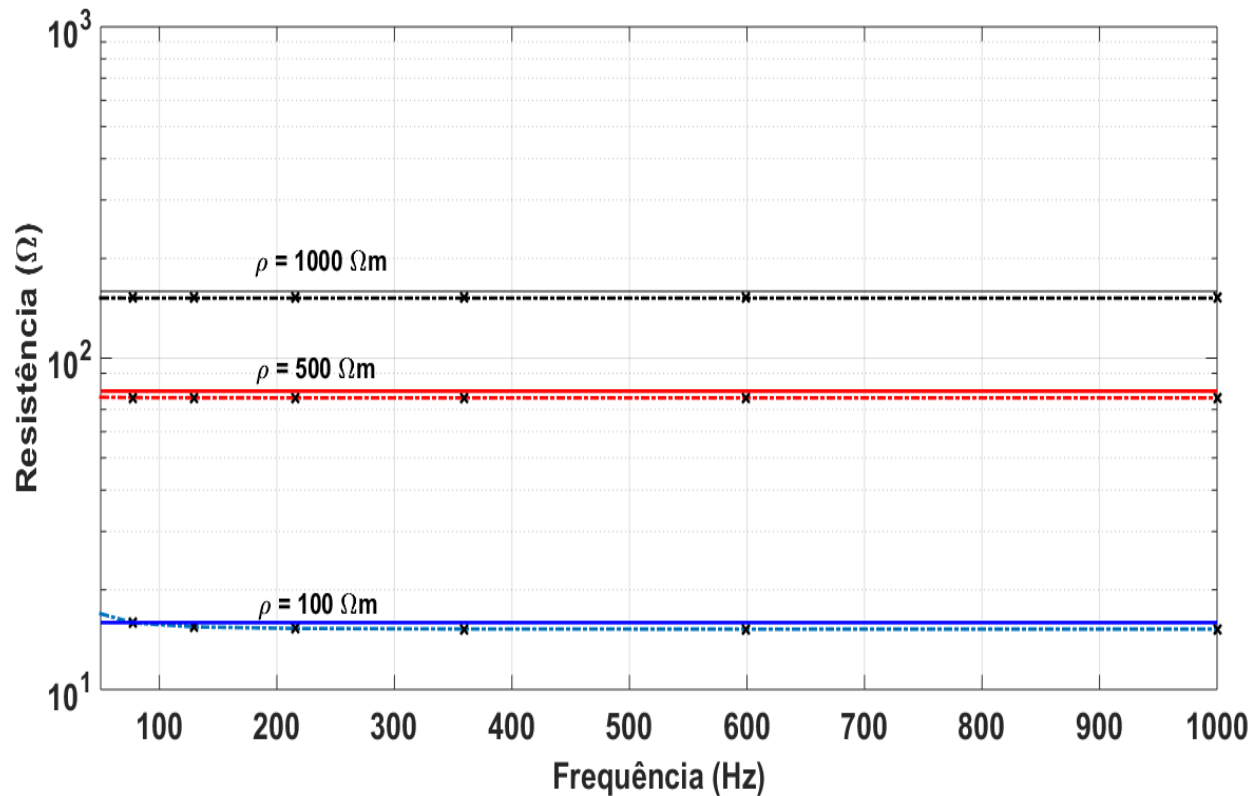
- Semiesfera- A resistência de aterramento da semiesfera é calculada pelo MoM e comparada com a equação clássica.
- Eletrodo Vertical- impedância de aterramento é calculada pelo MoM e comparada com o modelo a parâmetros distribuídos (TLM).



(a)

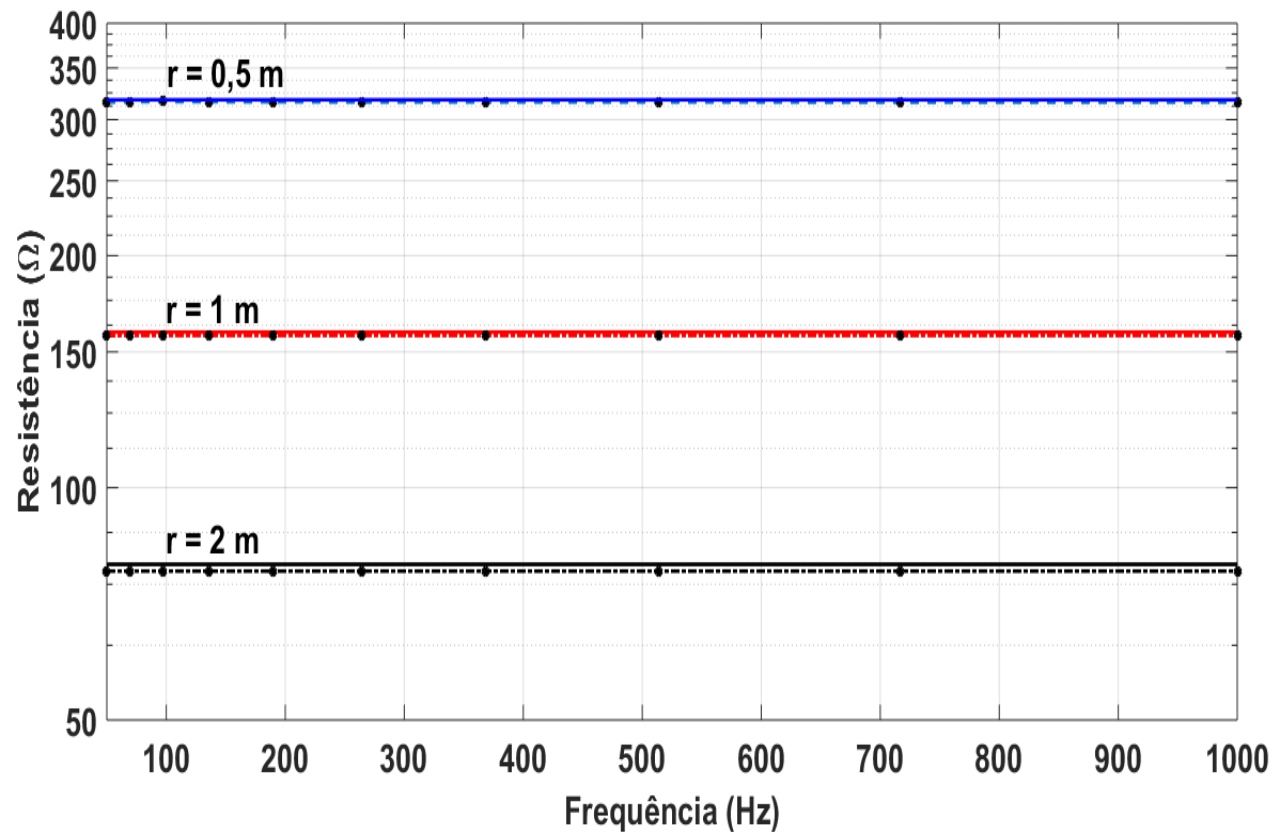
$$R_T = \frac{\rho}{2\pi a}$$

O raio do eletrodo semiesférico é mantido constante $a=1$ m e as resistividades de 100, 100 e 2000 Ohmm.

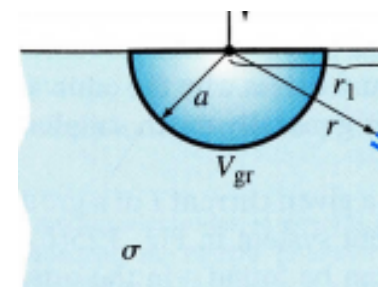


Resistividade	MoM	Equação (79)	Erro (%)
$\rho = 100 \Omega \text{ m}$	15,29 Ω	15,90 Ω	3,8365
$\rho = 500 \Omega \text{ m}$	75,94 Ω	79,50 Ω	4,4780
$\rho = 1000 \Omega \text{ m}$	151,8 Ω	159 Ω	4,5280

A resistividade do solo é constante $\rho=1000 \Omega\text{m}$ e os raios dos eletrodos são 0,5 m, 1 m e 2 m.



Raio	MoM	Equação (79)	Erro (%)
$a = 0,5 \text{ m}$	316,6 Ω	318,3 Ω	0,534
$a = 1 \text{ m}$	157,5 Ω	159,2 Ω	1,067
$a = 2 \text{ m}$	77,97 Ω	79,58 Ω	2,023



Home Construct Transform Source/Load Request Mesh Solve/Run Tools View Display options

Zoom area, Zoom in, Zoom to extents, Zoom out, Panning mode, Rotate, Isometric, Top, Bottom, Front, Back, Left, Right, Transform view, Vertical z axis, Depth lighting, Undo view, Redo view, 3D mouse, 3D view, Schematic, Notes, File, Cascade, Close, Close all, Close other, Tree, Messages, Show

Configurations

StandardConfiguration1

Construction Configuration

StandardConfiguration1

- Definitions
 - Variables
 - a = 12.5/1000
 - c0 = 1/sqrt(eps0*mu0)
 - eps0 = 8.85418781761e-12
 - epsR = 10
 - freq1 = 100
 - freq2 = 10e6
 - gap = 3e-2
 - L = 3
 - mu0 = pi*4e-7
 - pi = 3.14159265358979323846
 - sigma = 1/1000
 - zfo = sqrt(mu0/eps0)
 - Media
 - Workplanes
 - Global
 - Frequency [100 Hz, 101.159 Hz, ..., 9.88...]
 - Sources
 - VoltageSource1
 - Configuration specific
 - Requests

Solution frequency

Frequency | Export | Advanced

Logarithmically spaced discrete points

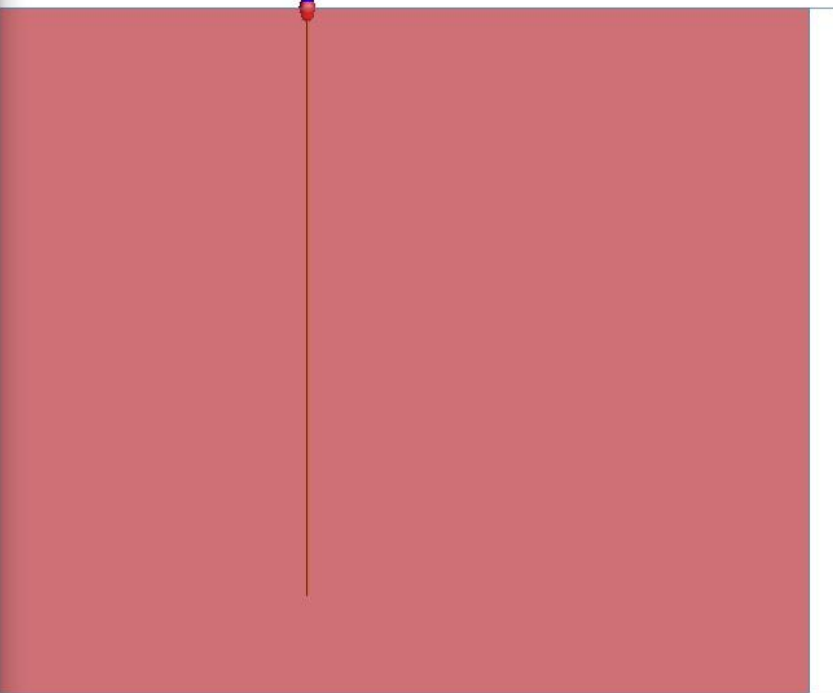
Start frequency (Hz)

End frequency (Hz)

Number of frequencies

Interval factor

OK Cancel



Opening project file...

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C:\Users\Anderson\Downloads\

Modifying variable...

Modified variable "a" from (0.5*15.87/1000) to (12.5/1000)

Configurations

StandardConfiguration1

Configuration

StandardConfiguration1

Definitions

Variables

- $a = 12.5/1000$
- $c0 = 1/\sqrt{\epsilon_0 \mu_0}$
- $\epsilon_0 = 8.85418781761e-12$
- $\epsilon_0 R = 10$
- $\text{freq1} = 100$
- $\text{freq2} = 10e6$
- $\text{gap} = 3e-2$
- $L = 3$
- $\mu_0 = \pi \cdot 4e-7$
- $\pi = 3.14159265358979323846$
- $\sigma = 1/1000$
- $z0 = \sqrt{\mu_0/\epsilon_0}$

Media

Workplanes

Global

- Frequency [100 Hz, 101.159 Hz, ..., 9.88...]

Sources

- VoltageSource1

Configuration specific

- Requests

Create mesh

Options Advanced

Scope

All Selection

Global mesh sizes

Mesh size Custom ?

Triangle edge length

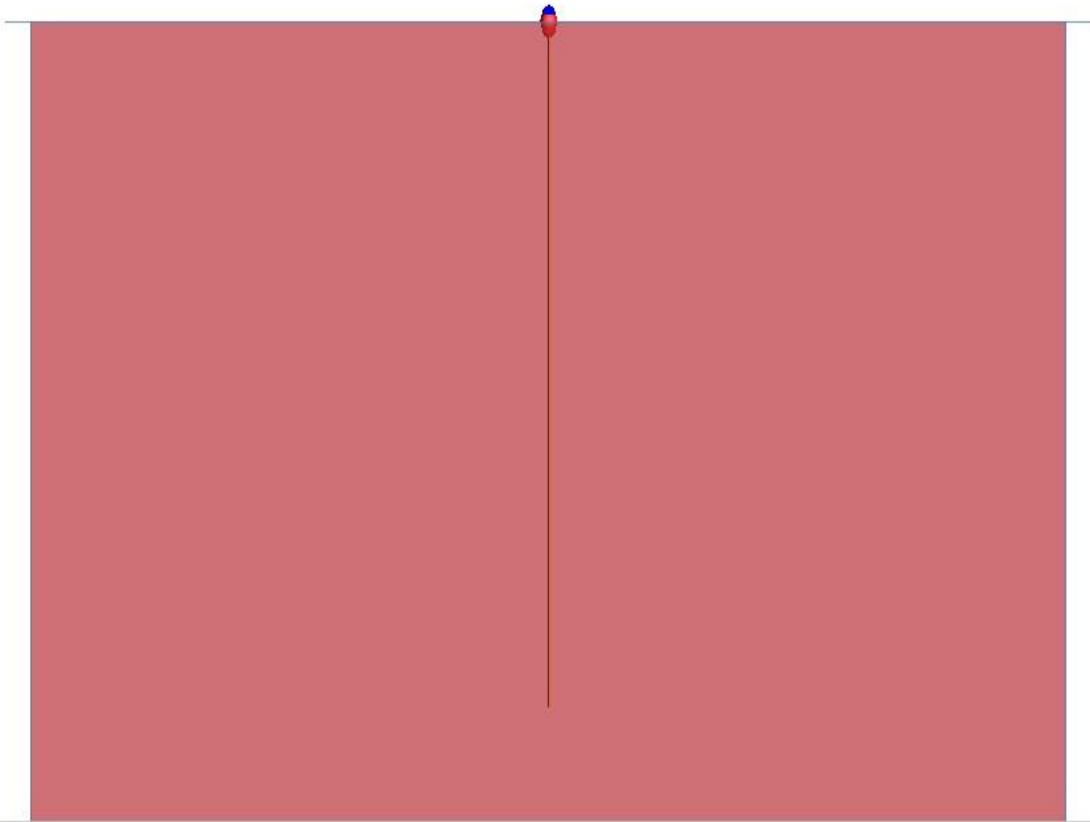
Wire segment length L/20

Tetrahedron edge length

Global wire radius

Wire segment radius a/4

Mesh Store settings Cancel



3D View

Home Time analysis Reporting View Display Mesh Result Animate

Cutplanes Greyscale Boundary Annotation type

Top left Top right Bottom left Bottom right Individual range Legend text

Sources Loads Cables Networks Probes TX line Points RX antenna

Symmetry Array base element PBC FDTD boundary type

Plane Opacity

Main axes Tick marks Mini axes

Object Browser

vertical_wire_segment_soil_halfspace_and_infin...

Browser

Results

StandardConfiguration1 [100 Hz, 101.15...]

Media

- Dielectric
 - Ground
 - ground2
- Perfect electric conductor
- Perfect magnetic conductor
- Free space

Mesh model

- Feko Mesh

Excitations

- VoltageSource1

Requests

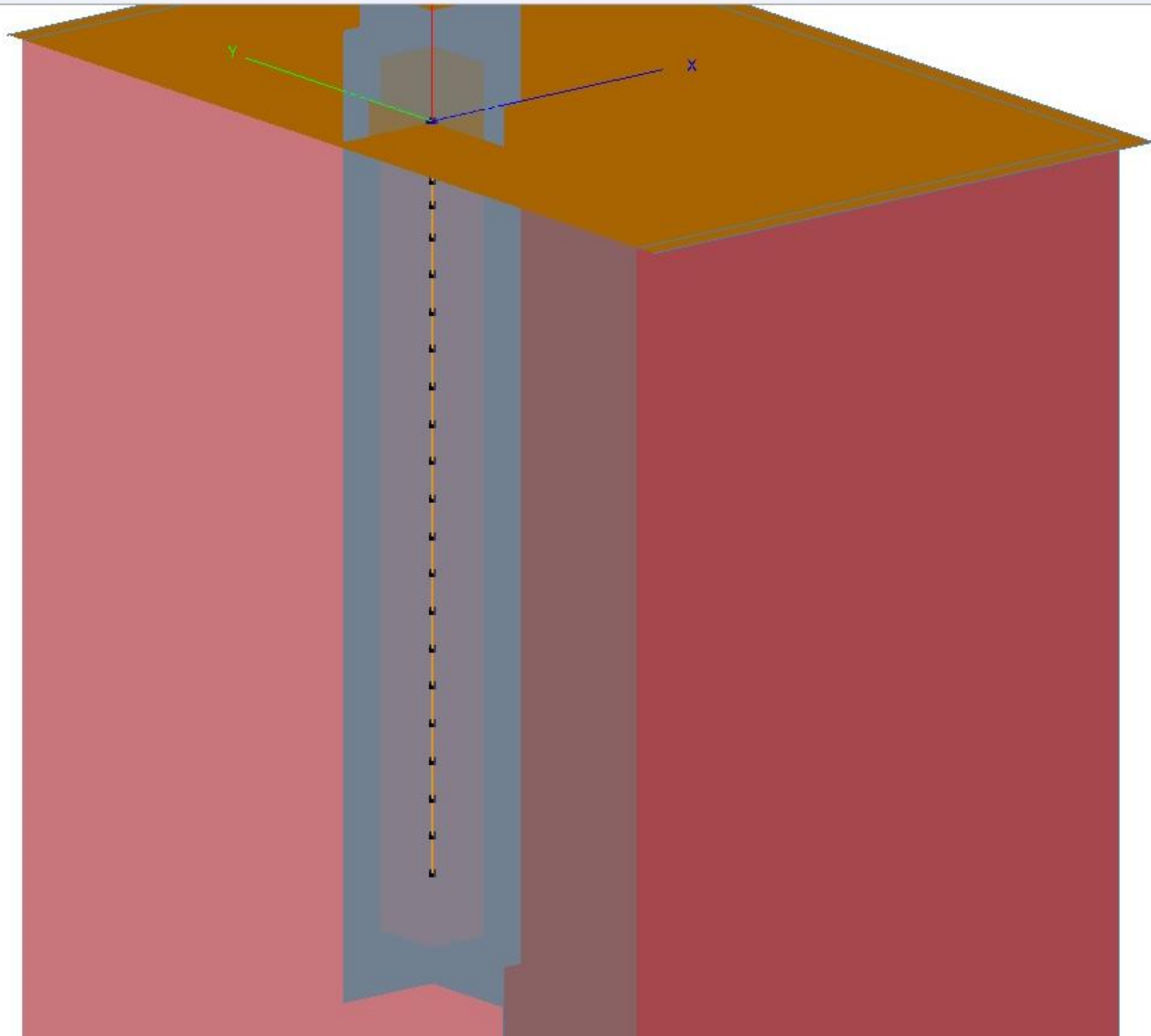
- Power

Plane / ground

- InfiniteSubstrate

Is Browser

ty	Value



vertical_wire_segment_soil_halfspace_and_infin...

vertical_wire_segment_soil_halfspace_and_i...

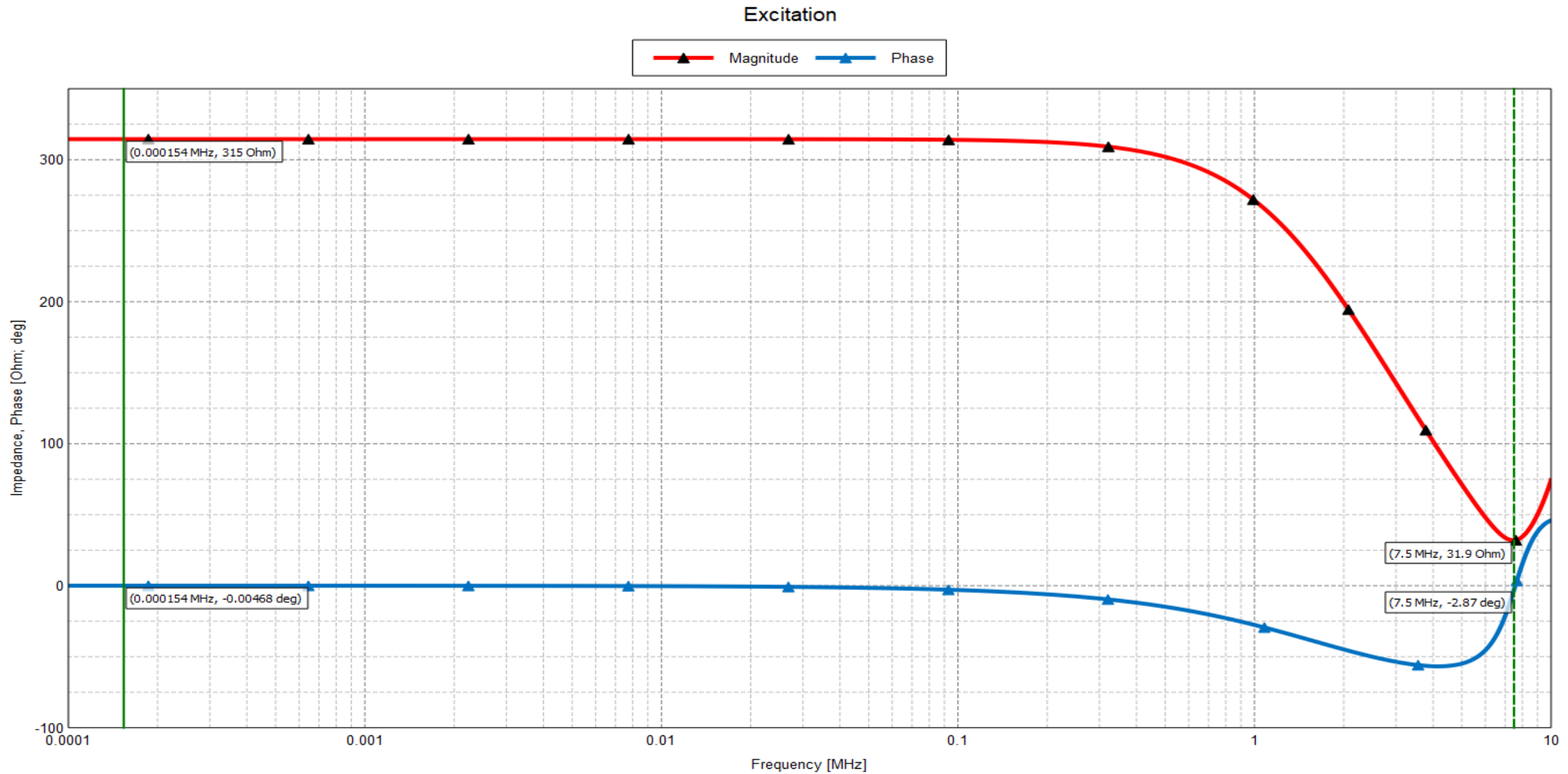
StandardConfiguration1

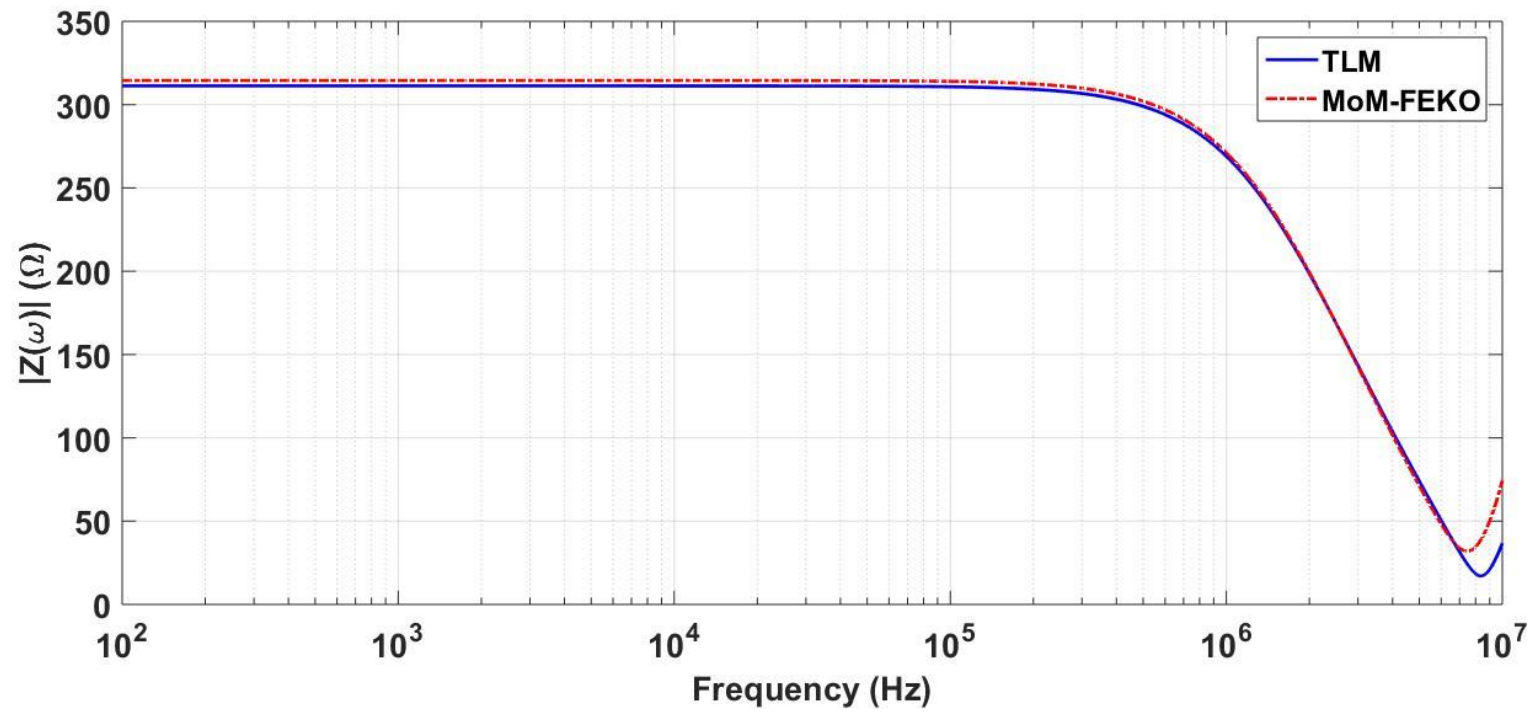
3D View results

None

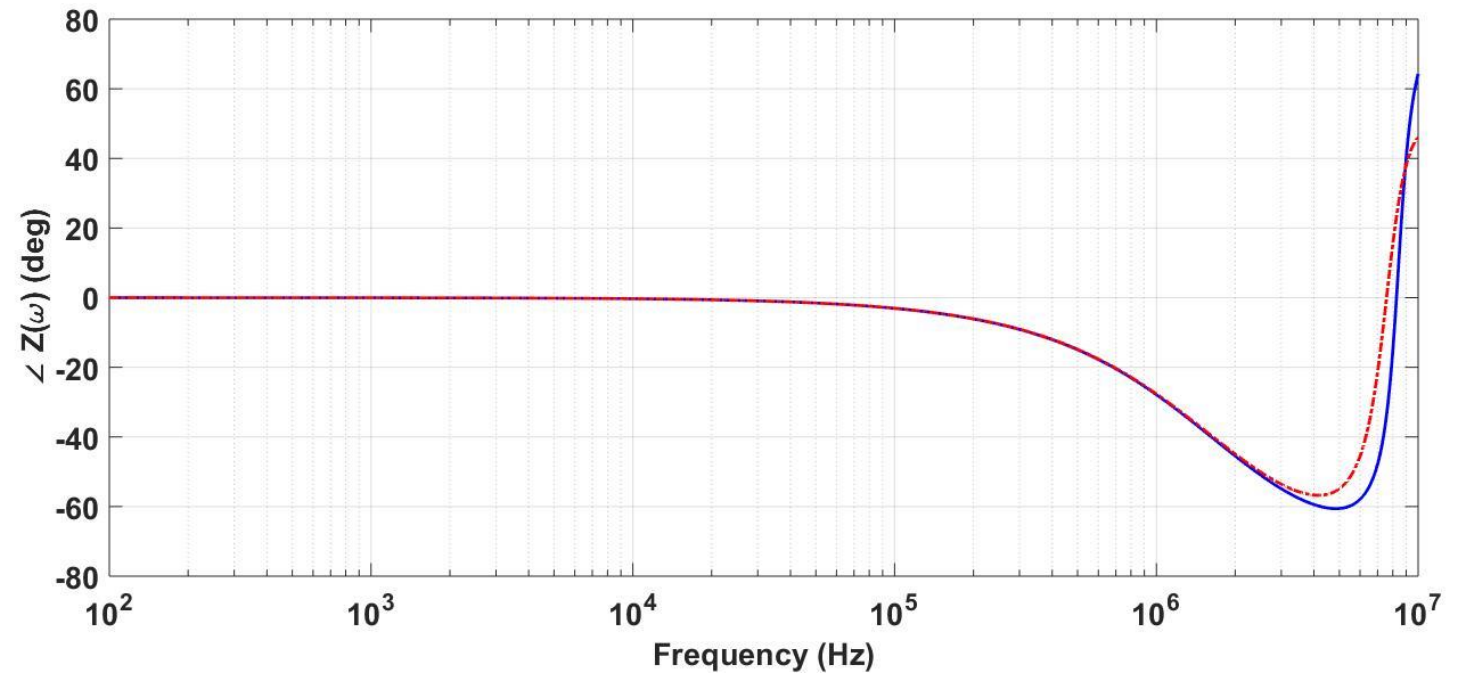
- Request
- Slice
- Quantity
- Maths

Impedância Eletrodo Vertical



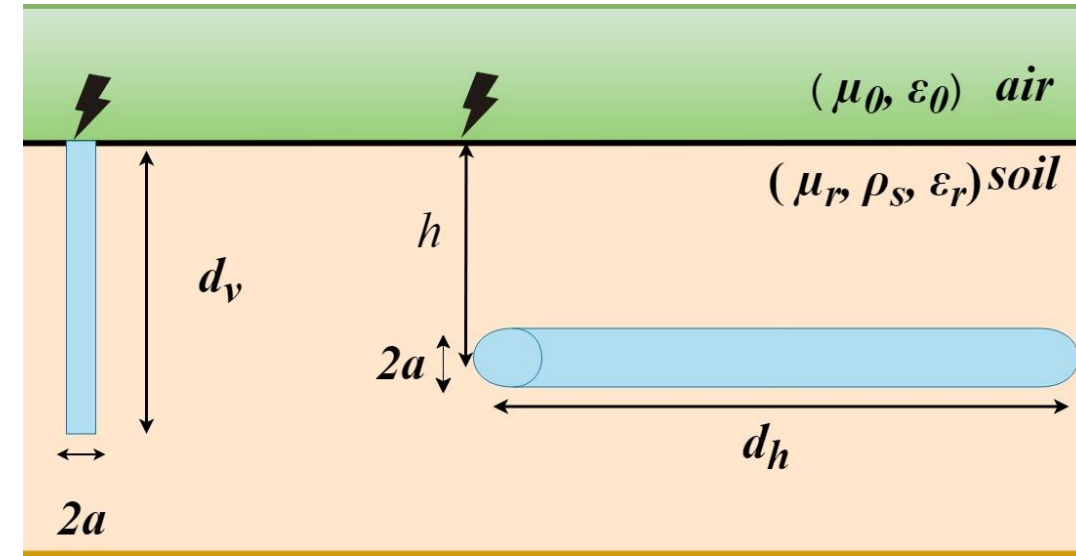
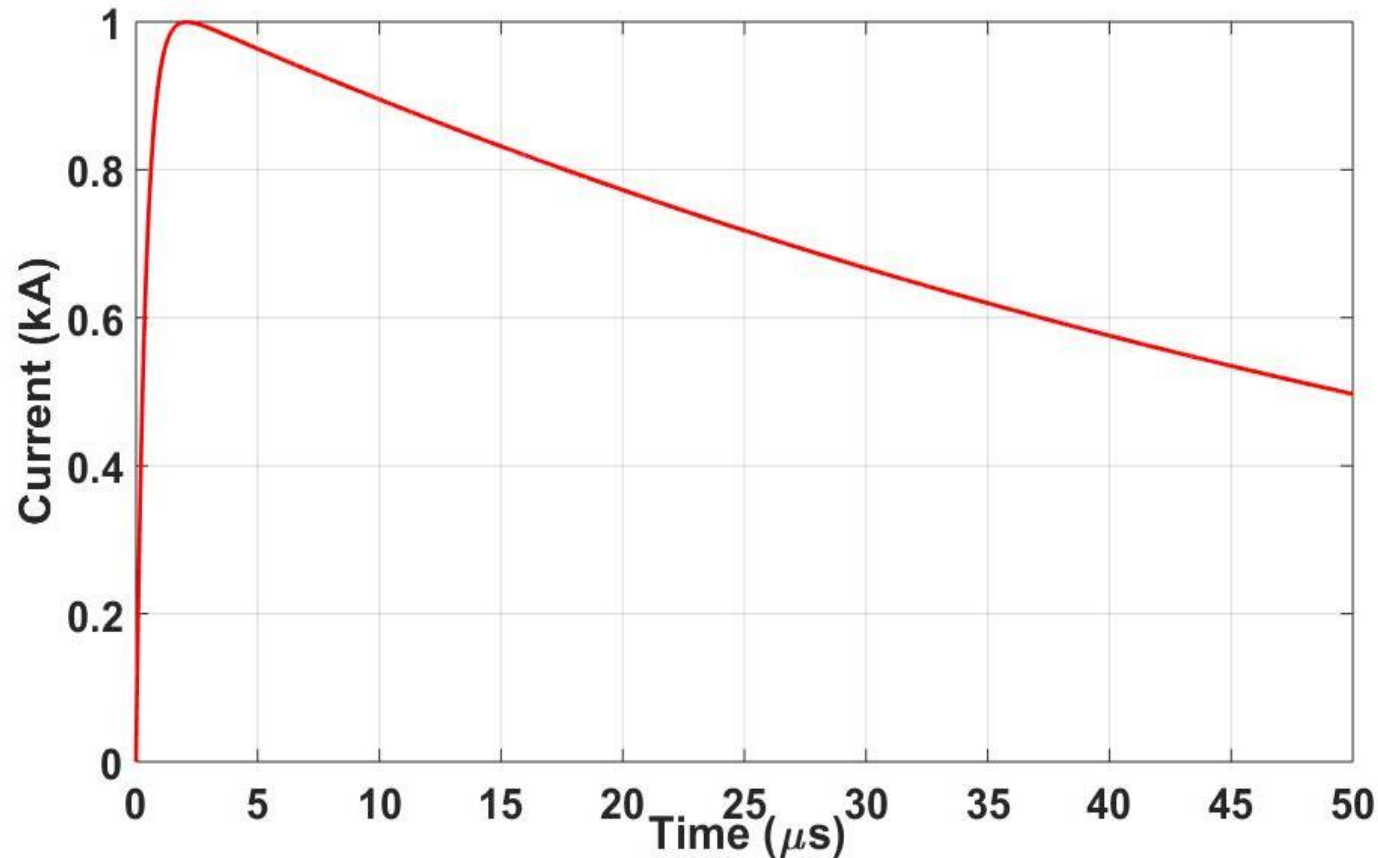


Comparação MoMxTLM

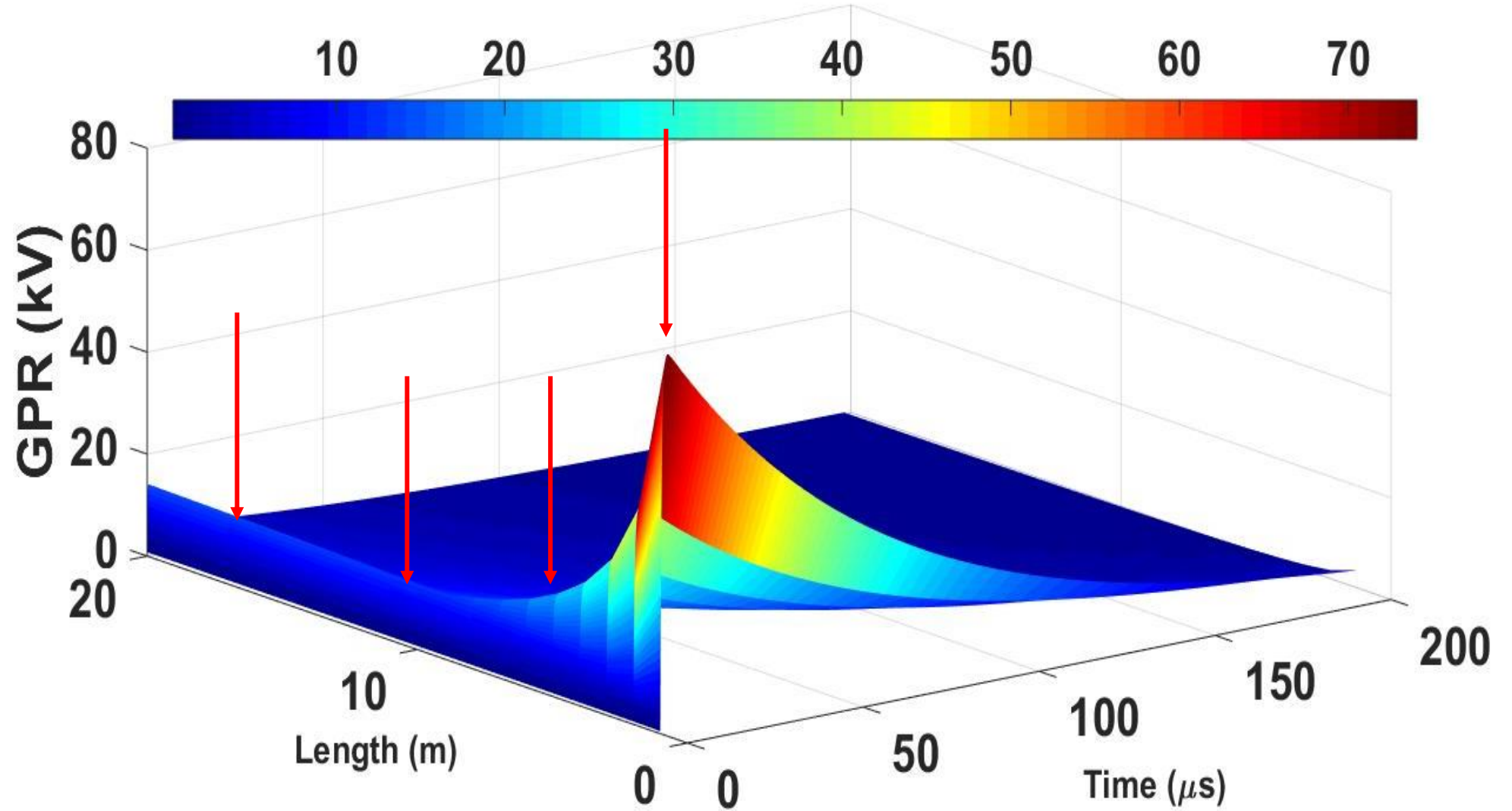


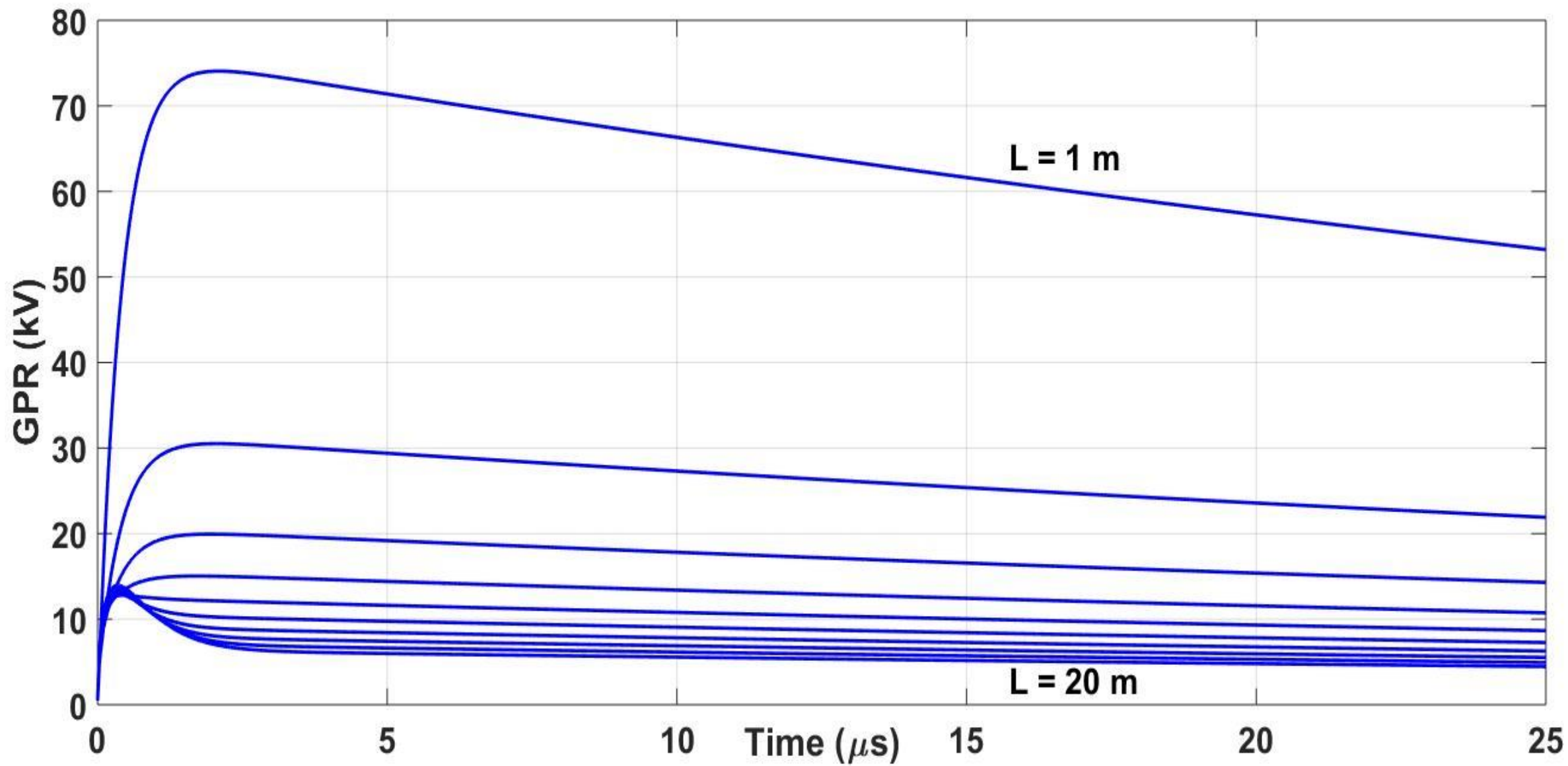
Impedância Impulsiva-Definição

$$V(t) = L^{-1}\{Z(s)I(s)\} = GPR$$



GPR para eletrodo vertical





Definição

- A impedância impultiva é definida por :

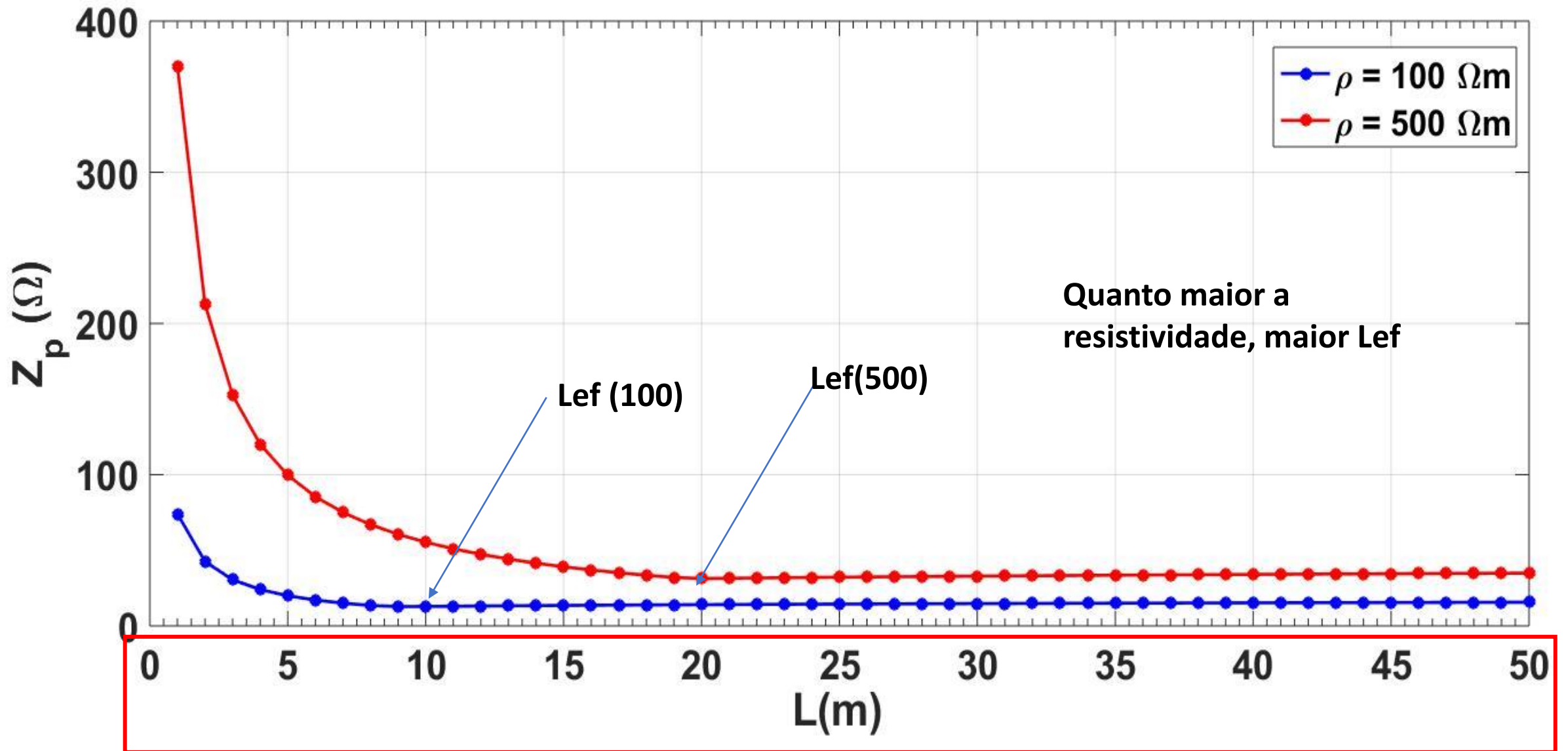
$$Z_p = \frac{V_p}{I_p}$$

Sendo:

V_p o valor de pico do GPR

I_p é o pico da corrente impulsive injetada no eletrodo.

Zp eletrodo vertical 1m-50m



Comprimento Efetivo

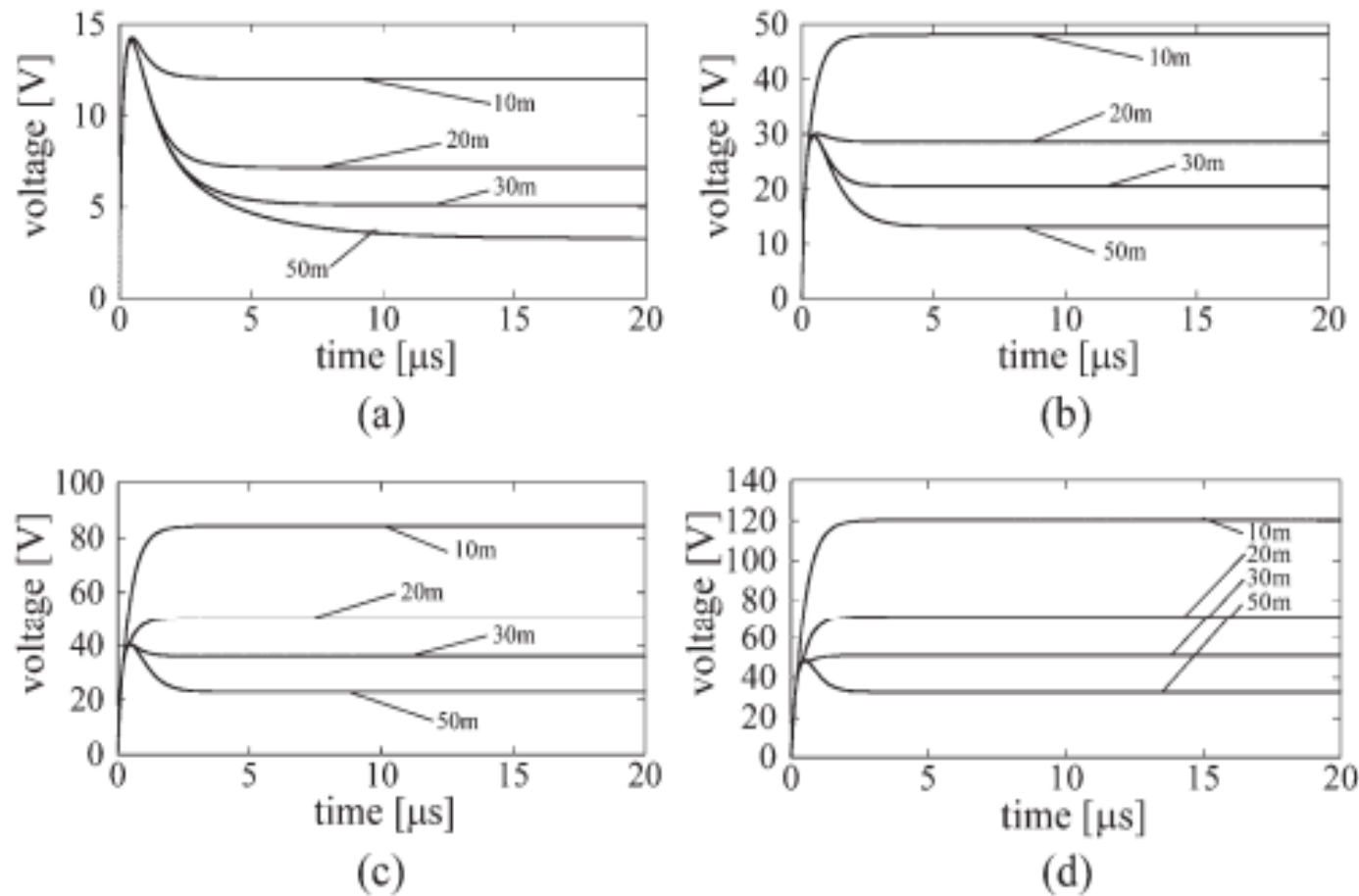
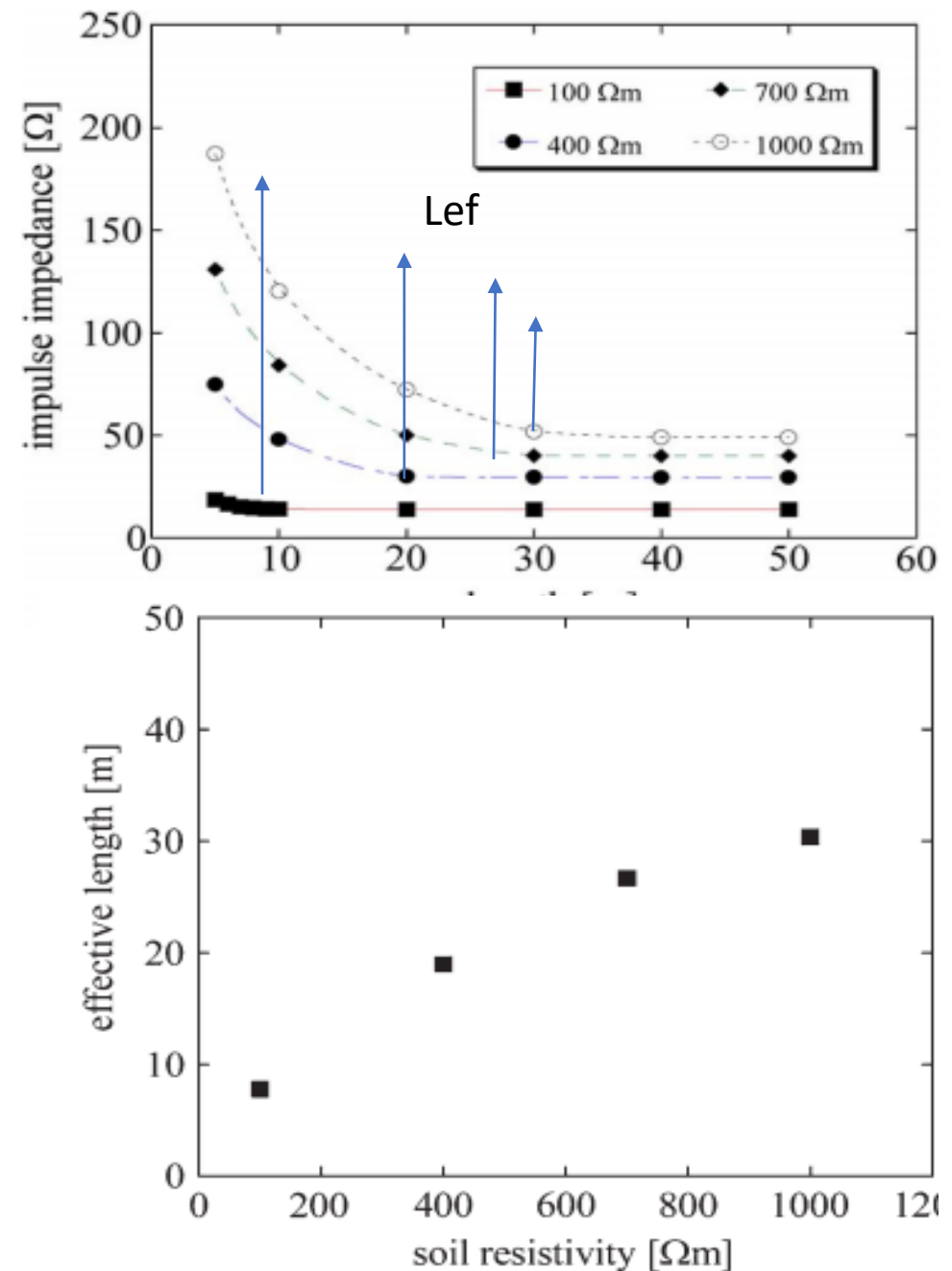


Fig. 6. Simulation result of the horizontal grounding electrode with changing soil resistivity. (a) 100 Ωm . (b) 400 Ωm . (c) 700 Ωm . (d) 1000 Ωm .



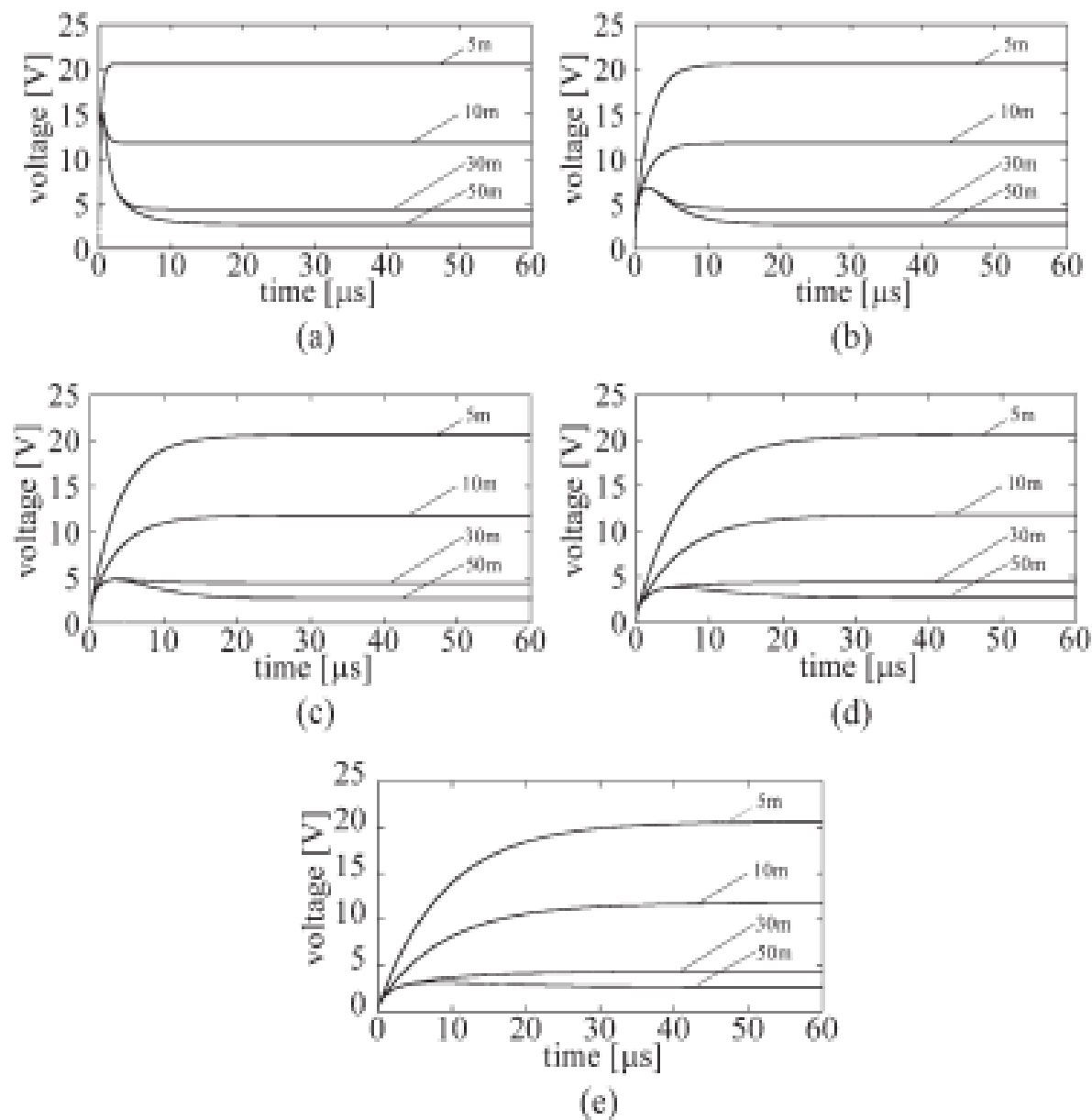
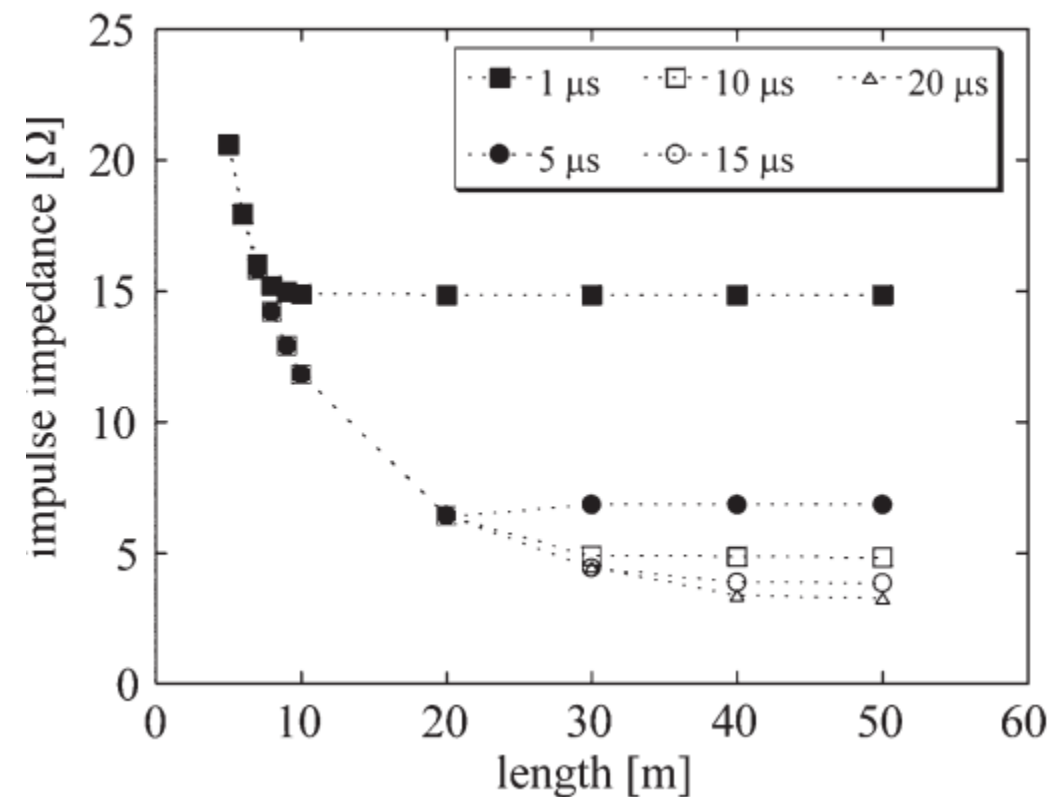


Fig. 11. Simulation result of vertical grounding rod with changing wavefront time of the injected current. (a) $1 \mu\text{s}$. (b) $5 \mu\text{s}$. (c) $10 \mu\text{s}$. (d) $15 \mu\text{s}$. (e) $20 \mu\text{s}$.



Derivations of Effective Length Formula of Vertical Grounding Rods and Horizontal Grounding Electrodes Based on Physical Phenomena of Lightning Surge Propagations

Kazuo Yamamoto, *Member, IEEE*, Shinichi Sumi, Shozo Sekioka, *Member, IEEE*, and Jinliang He, *Fellow, IEEE*

- O comprimento efetivo é importante para não se investir em material, imaginando melhorar o desempenho do eletrodo (para correntes impulsivas de altas frequências) aumentando-se desnecessariamente seu comprimento (↓ custo)[1].

[1]-UMA PROPOSTA DE REPRESENTAÇÃO DE SISTEMAS DE ATERRAMENTO DIRETAMENTE NO DOMÍNIO DO TEMPO-Claudiner Mendes de Seixas, Dissertação, UNESP,2017.

Variação dos Parâmetros do solo com a Frequência

- Interpretação física;
- Fórmulas;
- Simulações: Impedância de aterramento com parâmetros dependentes e constante do solo;
- GPR para os parâmetros dependentes e constante do solo;

Medição GPR para uma eletrodo vertical

Diversas equações são propostas na literatura, baseadas em ensaios de laboratório com amostras de solo.

Dada a complexidade na composição do solo, não há uma formulação universal para a permissividade e resistividade do solo.

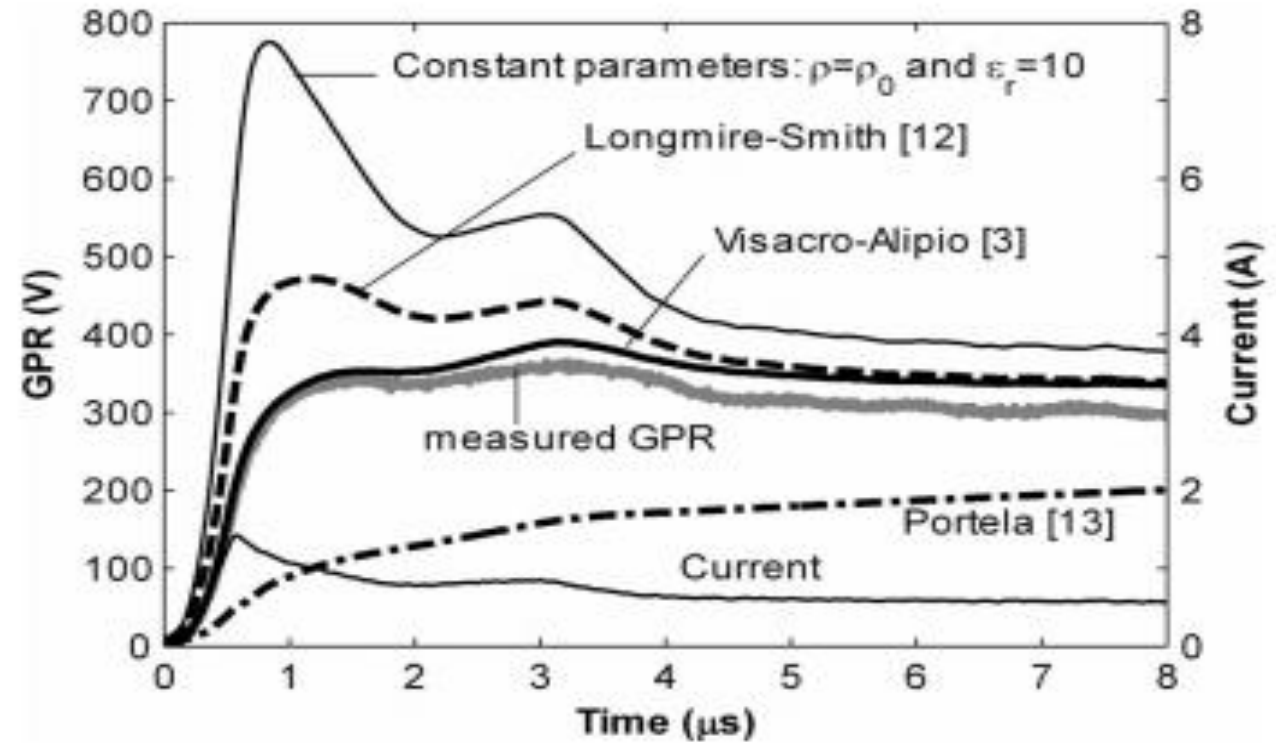


Fig. 1. Comparison of the measured and simulated GPRs of a 3-m vertical rod (8.65-mm radius) developed in response to the impression of an impulsive current with front-time of $\sim 0.7 \mu\text{s}$ buried in soil with low-frequency resistivity $\rho_0 = 2000 \Omega\cdot\text{m}$. Measurements were developed following the same procedure in [4] and [14]. Simulations were implemented using an accurate electromagnetic model [15].

Modeling the Frequency Dependence of Electrical Parameters of Soil

Polarização

The total electric current density (\vec{J}_T) in a medium due to the impression of an external electric field (\vec{E}) is related with the curl of the magnetic field (\vec{H}) by Ampere–Maxwell’s law:

$$\vec{\nabla} \times \vec{H} = \sigma_0 \vec{E} + j\omega \epsilon \vec{E} = \vec{J}_C + \vec{J}_D = \vec{J}_T. \quad (1)$$

In (1), σ_0 is the ordinary low-frequency conductivity due to free ions or electrons, which gives a measure of the material ability to transport electric charges and also of the losses associated with the conducting process. In contrast with σ_0 , which can be assumed a real number, the permittivity ϵ is a complex number given by the following equation:

$$\epsilon = \epsilon' - j\epsilon''. \quad (2)$$

The real parcel of permittivity (ϵ') expresses the material ability to be polarized and to store electric energy, while the imaginary parcel (ϵ'') is associated to the losses occurring during the polarization process. Such losses represent the part of energy of the applied field which is dissipated as heat because of friction experienced by the electric dipoles as they continuously move in response to the alternating field.

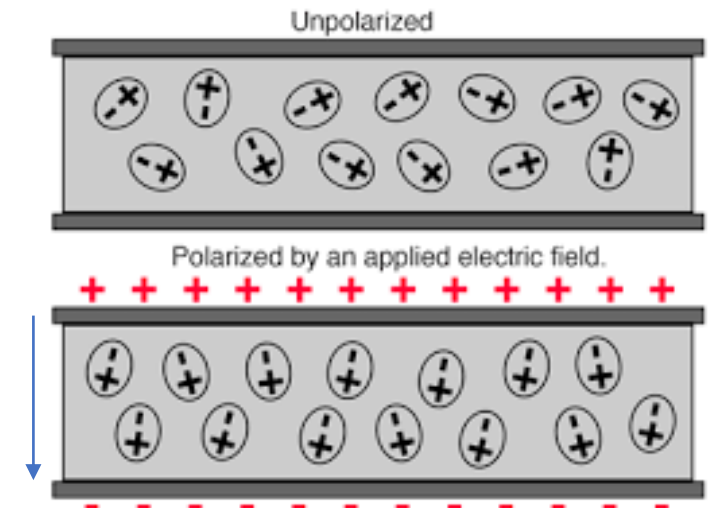
- <https://www.youtube.com/watch?v=KBJl1qiYOgo>

Aumento da condutividade real do solo

Considering the complex permittivity, (1) can be rewritten as:

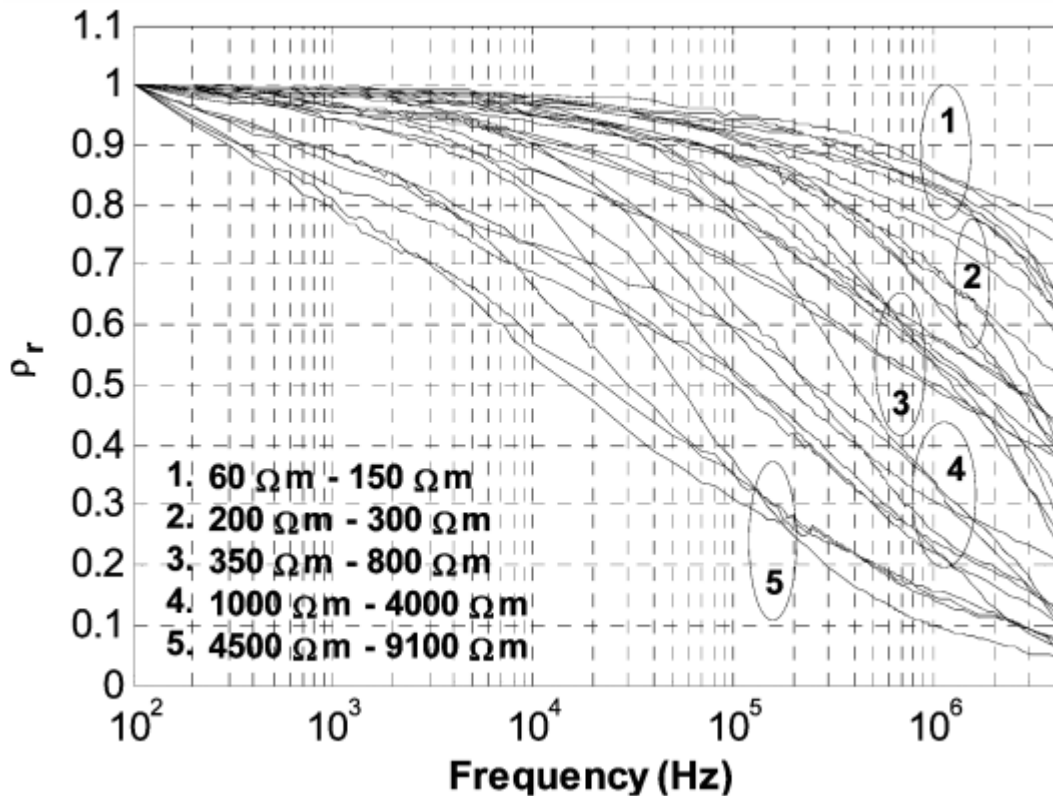
$$\begin{aligned} \vec{\nabla} \times \vec{H} &= \sigma_0 \vec{E} + j\omega (\epsilon' - j\epsilon'') \vec{E} \\ &= (\sigma_0 + \omega \epsilon'') \vec{E} + j\omega \epsilon' \vec{E} \\ &= \sigma \vec{E} + j\omega \epsilon' \vec{E} \end{aligned} \quad (3)$$

where σ represents the effective conductivity, comprising two components: a constant one related with free ions and electrons, and a frequency-dependent one related with losses due to polarization processes.



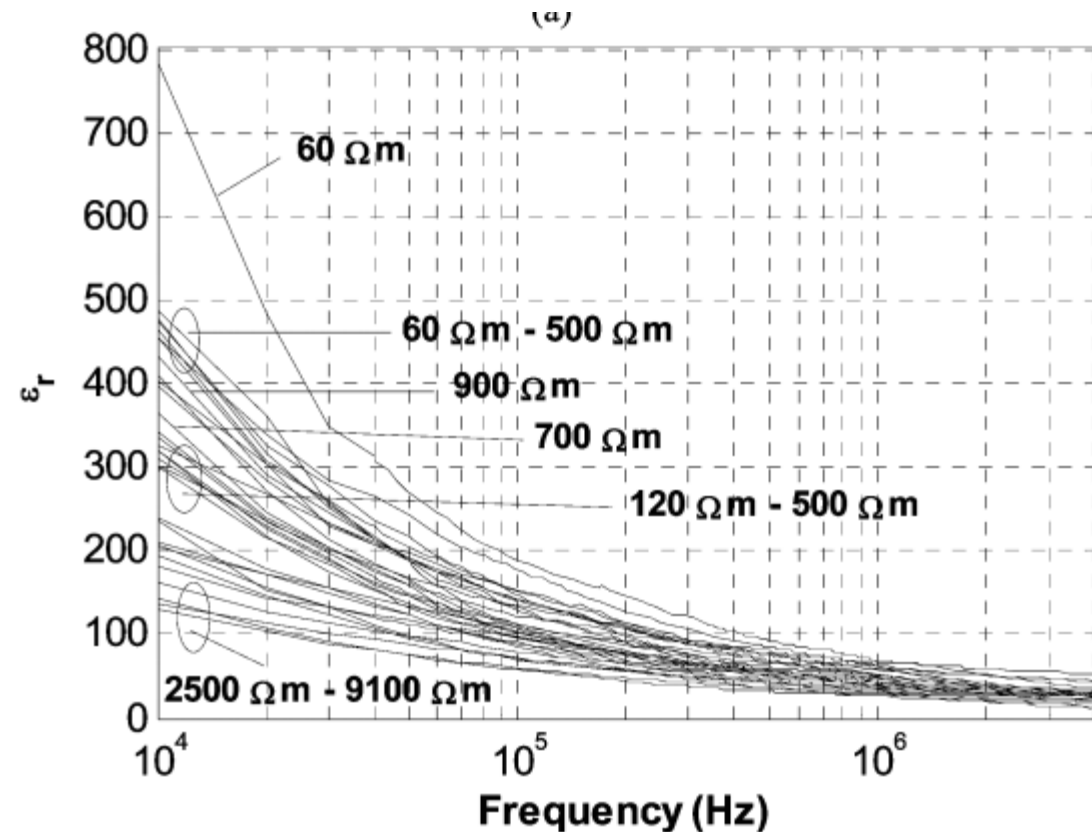
A. Measurements

The experimental methodology was applied to measure the parameters of soils distributed in 31 different sites in Brazil, most of them in Minas Gerais State. The soils, whose low-frequency resistivity ranges from 60 to 9100 Ωm , were measured within a 5-month period, in their natural conditions, including different moistures.



Frequency Dependence of Soil Parameters: Experimental Results, Predicting Formula and Influence on the Lightning Response of Grounding Electrodes

Silverio Visacro, *Member, IEEE*, and Rafael Alipio



Fórmulas para incluir o efeito da frequência nos parâmetros do solo

Visacro and Alípio

$$\rho(f) = \rho_0 \{1 + [1.2 \times 10^{-6}(\rho_0)^{0.73}] [(f - 100)^{0.65}]\}^{-1} \quad (1)$$

$$\varepsilon_r(f) = \begin{cases} 7.6 \times 10^3 f^{-0.4} + 1.30 & f \geq 10 \text{ kHz} \\ 192 & f < 10 \text{ kHz} \end{cases} \quad (2)$$

Longmire and Smith

$$\varepsilon_r(f) = \varepsilon_\infty + \sum_{n=1}^N \frac{a_n}{1 + \left(\frac{f}{f_n}\right)^2} \quad (4a)$$

$$\sigma(f) = \sigma_i + 2\pi\varepsilon_0 \sum_{n=1}^N a_n f_n \frac{(f/f_n)^2}{1 + (f/f_n)^2} \quad (4b)$$

Portela

$$\rho(f) = \left[\frac{1}{\frac{1}{\rho_0} + \Delta i [\cot \text{ang} \left(\frac{\pi}{2} \alpha\right)] \left(\frac{\omega}{2\pi \times 10^6}\right)^\alpha} \right]^{-1} \quad (3a)$$

$$\varepsilon(f) = \frac{\Delta i}{\omega} \left(\frac{\omega}{2\pi \times 10^6}\right)^\alpha \varepsilon_0 \quad (3b)$$

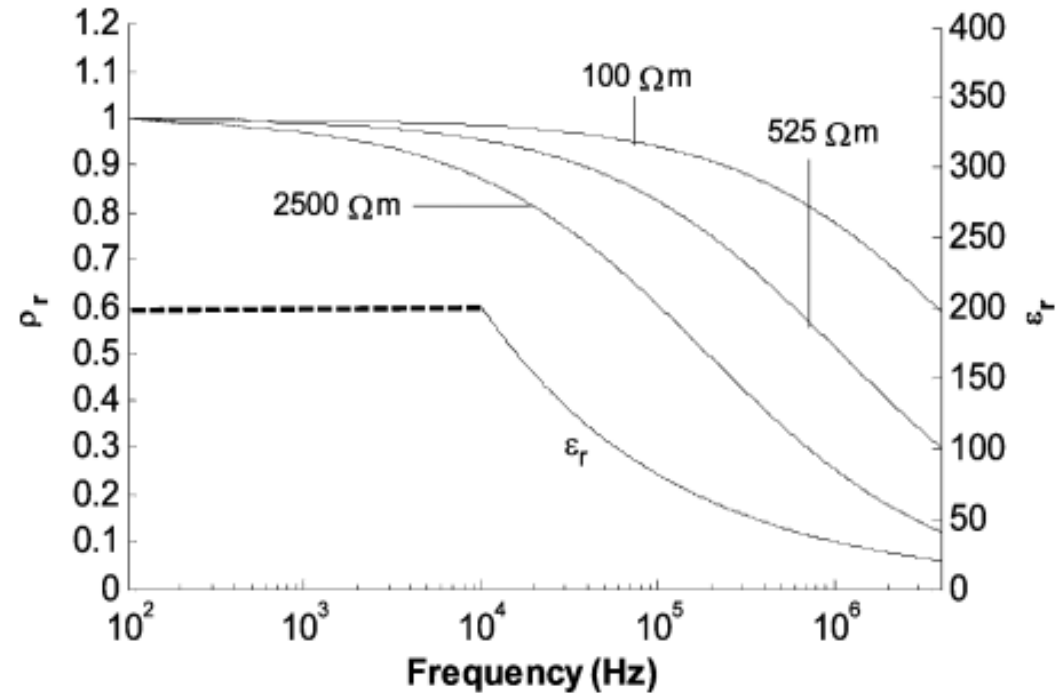
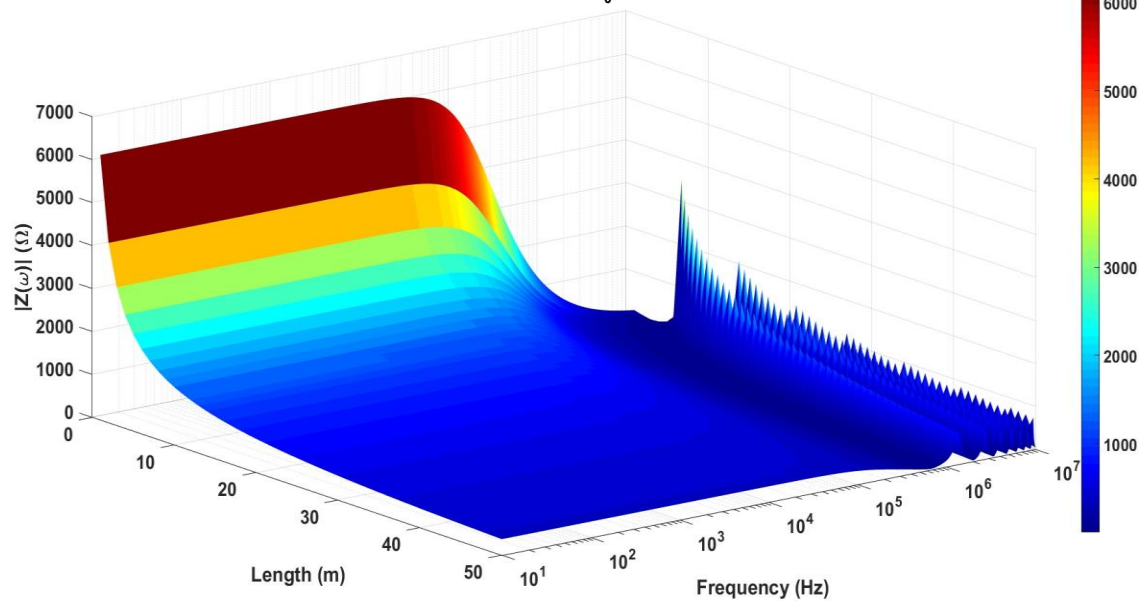
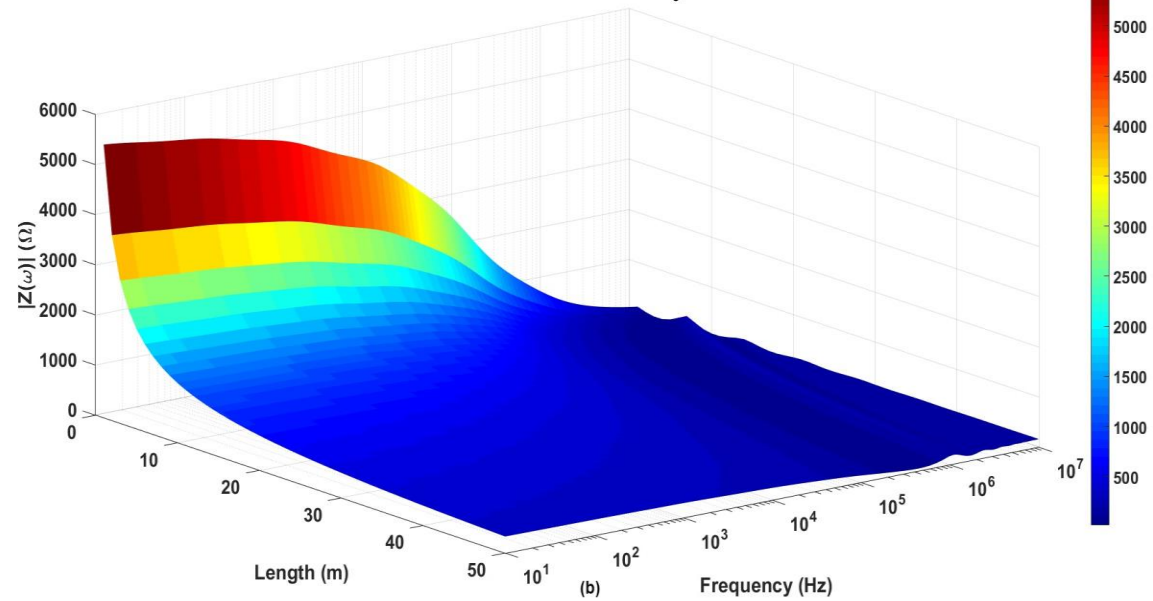


Fig. 10. Curve to represent the variation of the relative resistivity and relative permittivity as a function of frequency.

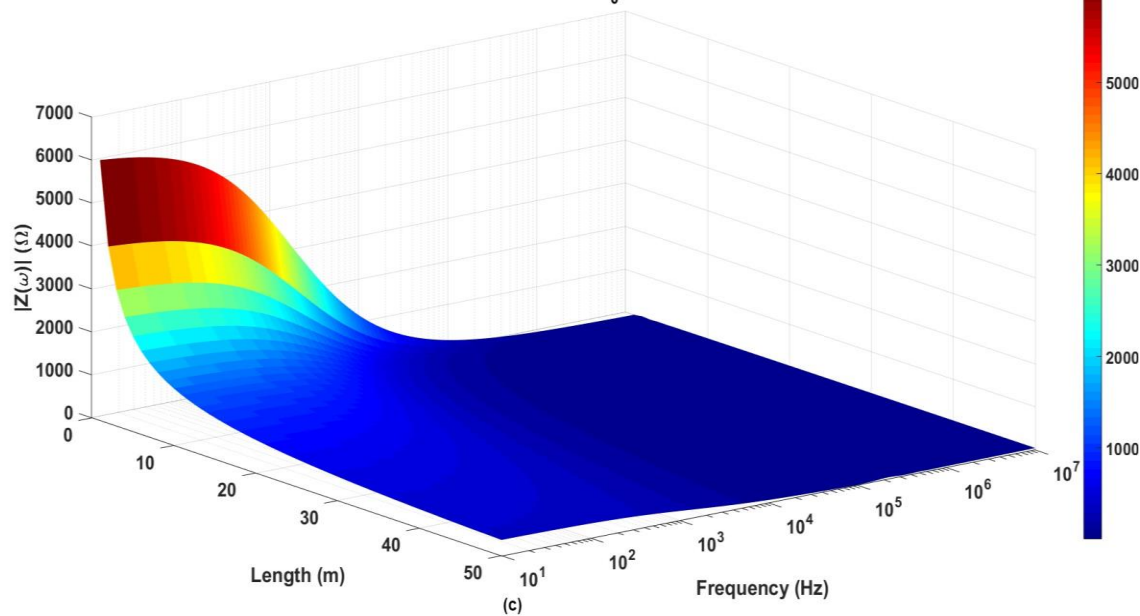
$|Z|$ with frequency-independent electrical parameters of soil
(constant parameters $\rho_0 = 10 \text{ k}\Omega\text{m}$)



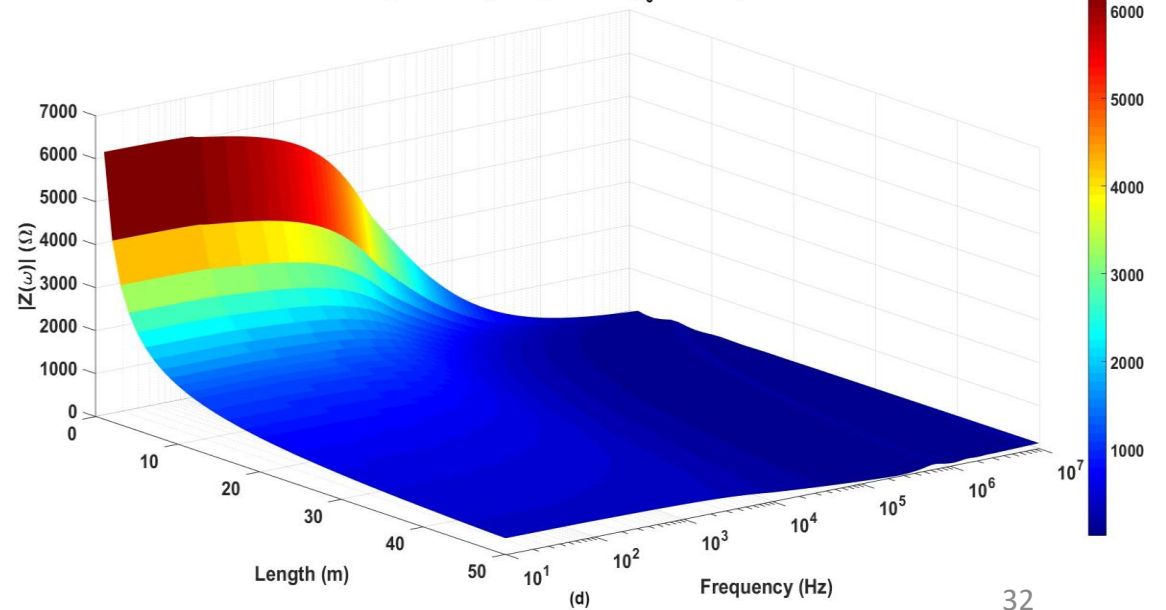
$|Z|$ with frequency-dependent electrical parameters of soil
(Longmire and Smith expressions $\rho_0 = 10 \text{ k}\Omega\text{m}$)



$|Z|$ with frequency-dependent electrical parameters of soil
(Portela expressions $\rho_0 = 10 \text{ k}\Omega\text{m}$)



$|Z|$ with frequency-dependent electrical parameters of soil
(Visacro-Alipio expressions $\rho_0 = 10 \text{ k}\Omega\text{m}$)



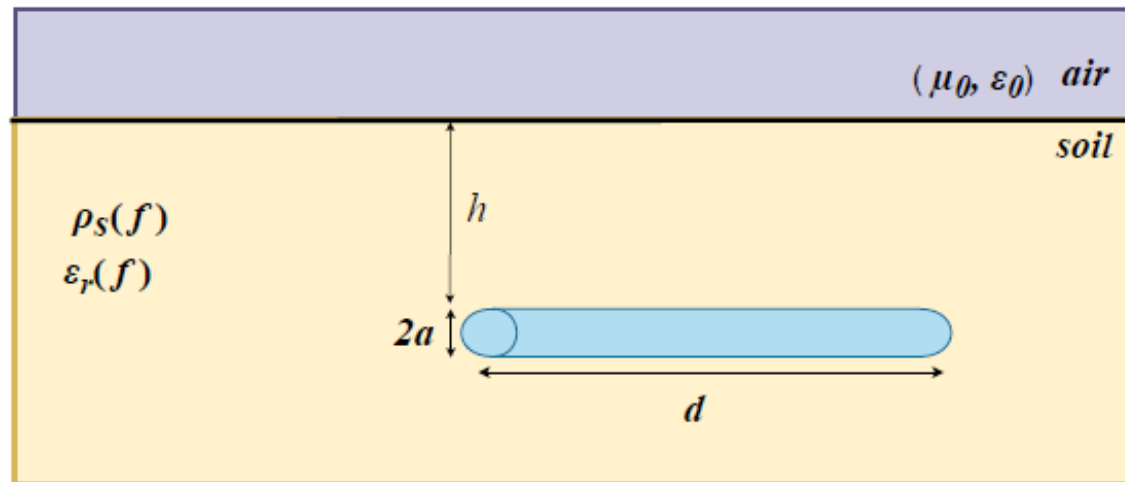
Exemplos

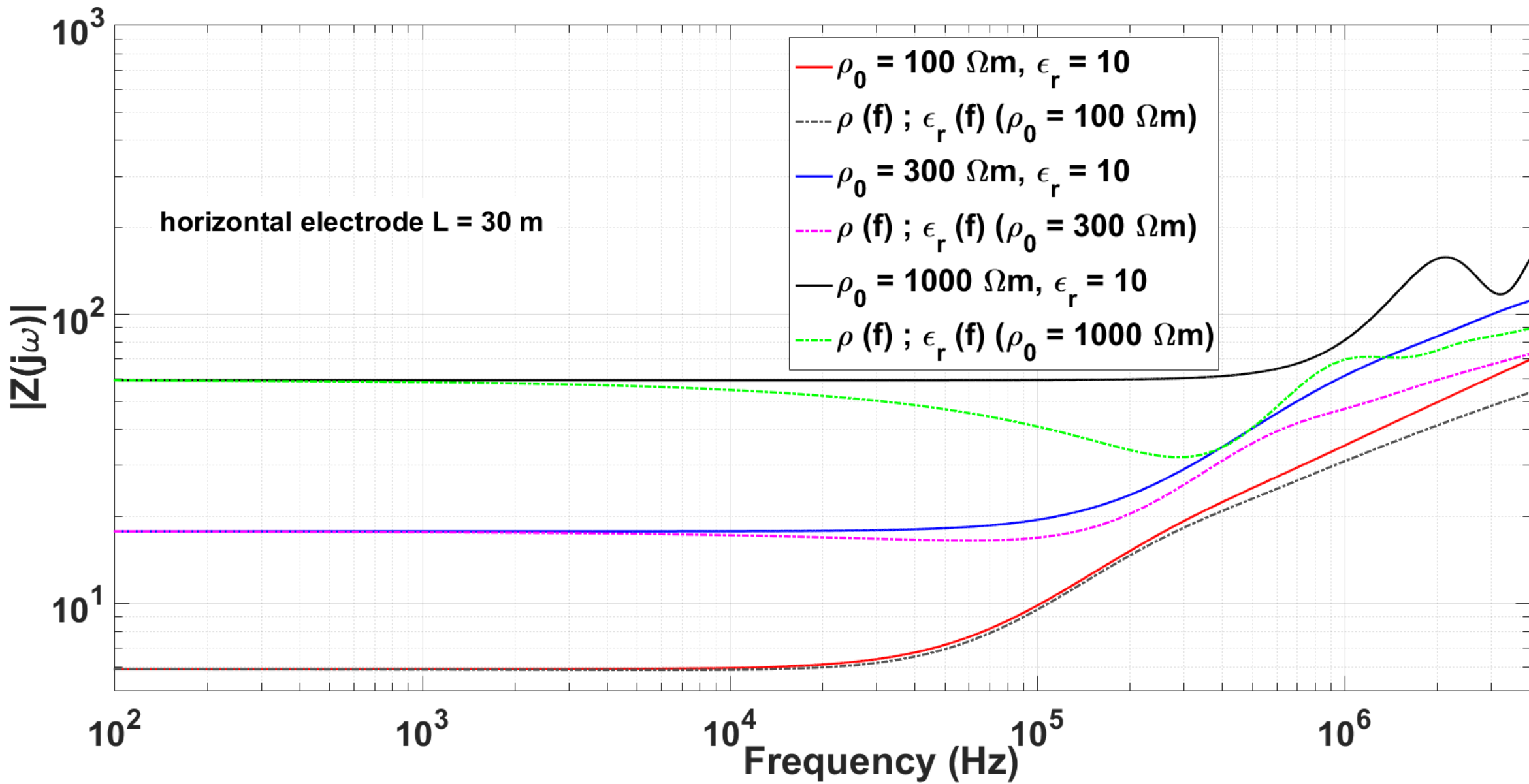
A dependência da frequência nos parâmetros do solo –permissividade ϵ e resistividade ρ são computada pelas equações propostas por Visacro and Alípio.

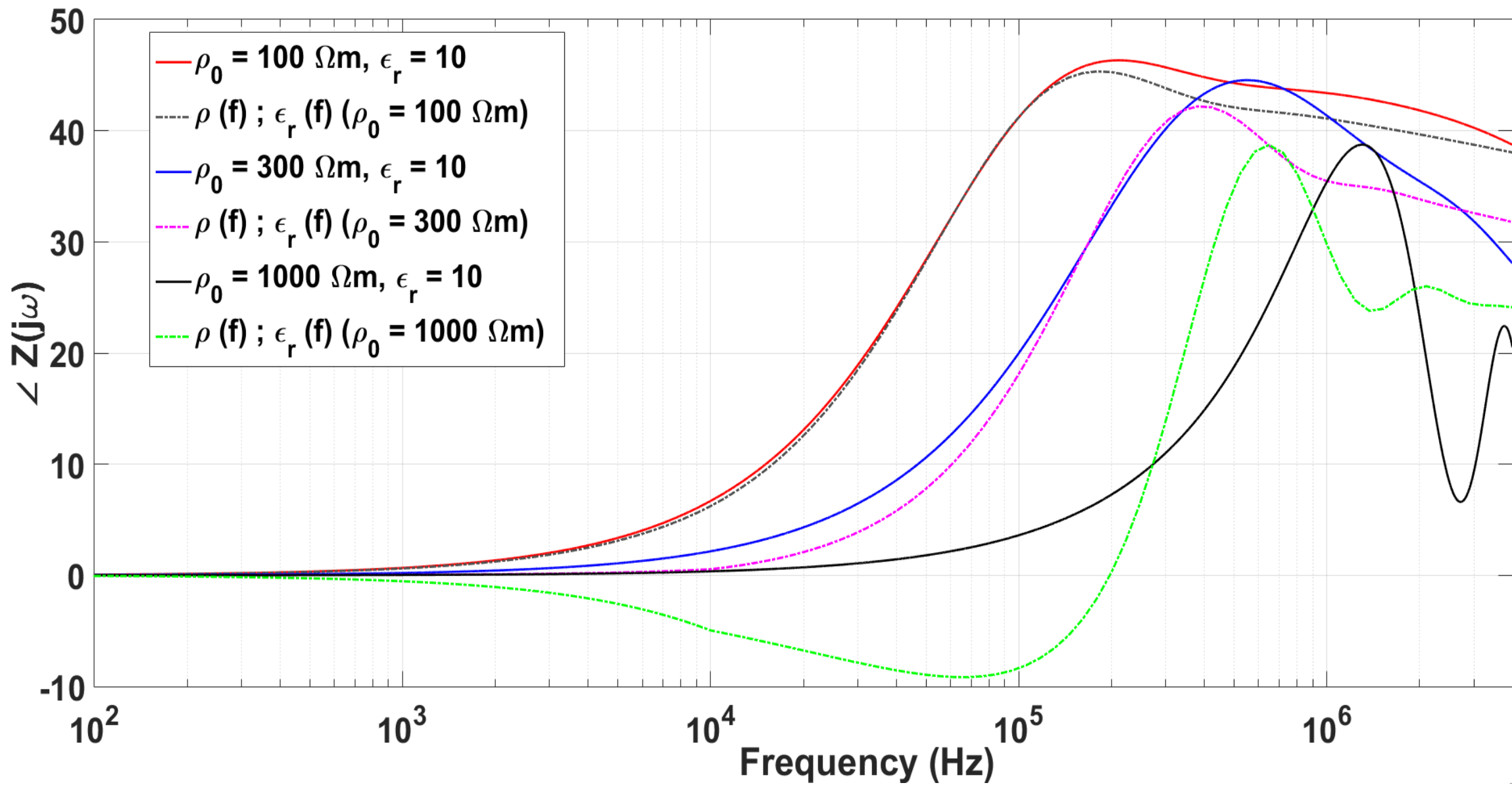
Parâmetros geométricos dos eletrodos: $d = 30$ m, $h = 1$ m $a = 12.5$ mm.

Parâmetros elétricos do solo: $\mu_0 = 0.4 \pi \mu$ H/m, $\epsilon_s = 10$ and $\rho_0 = 100, 300$ and $1,000 \Omega$ m.

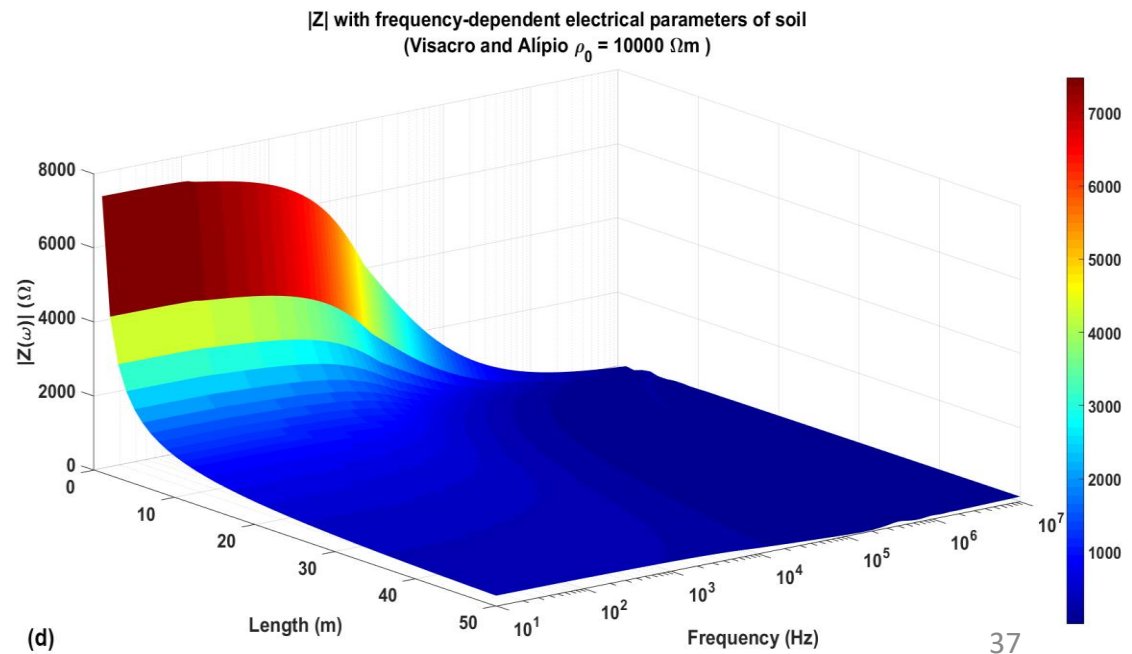
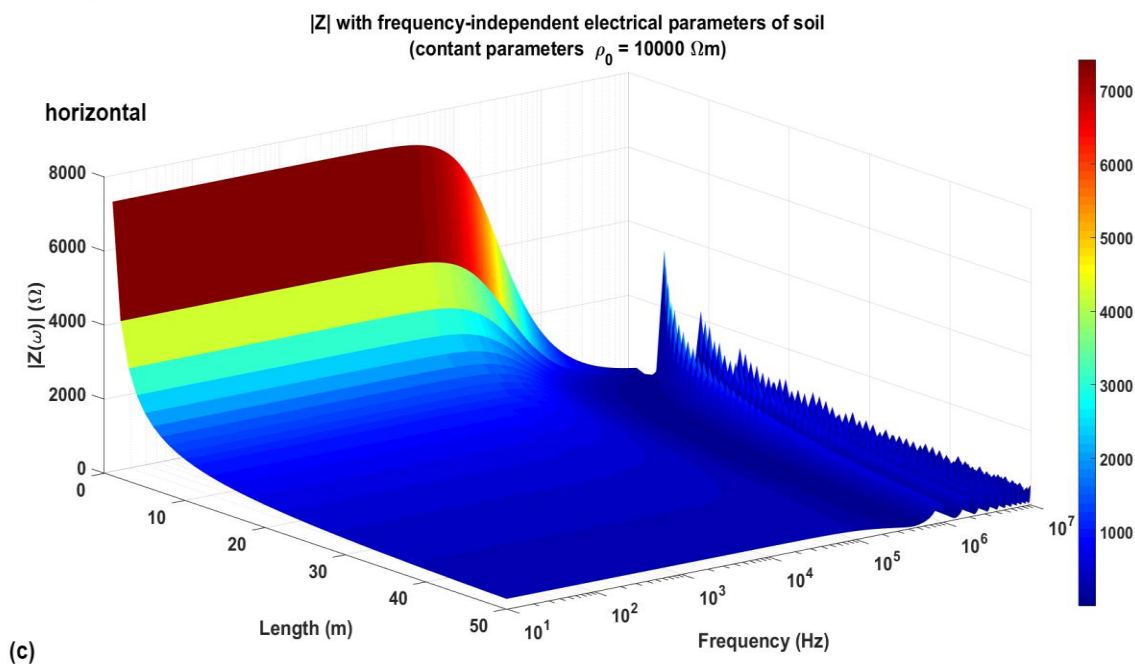
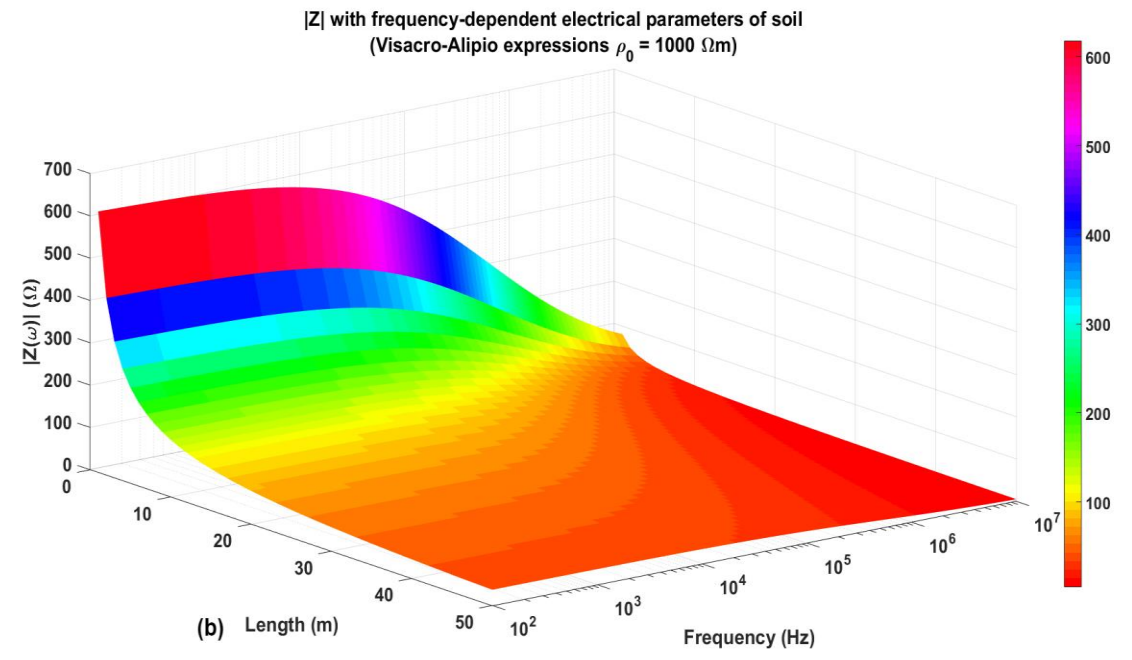
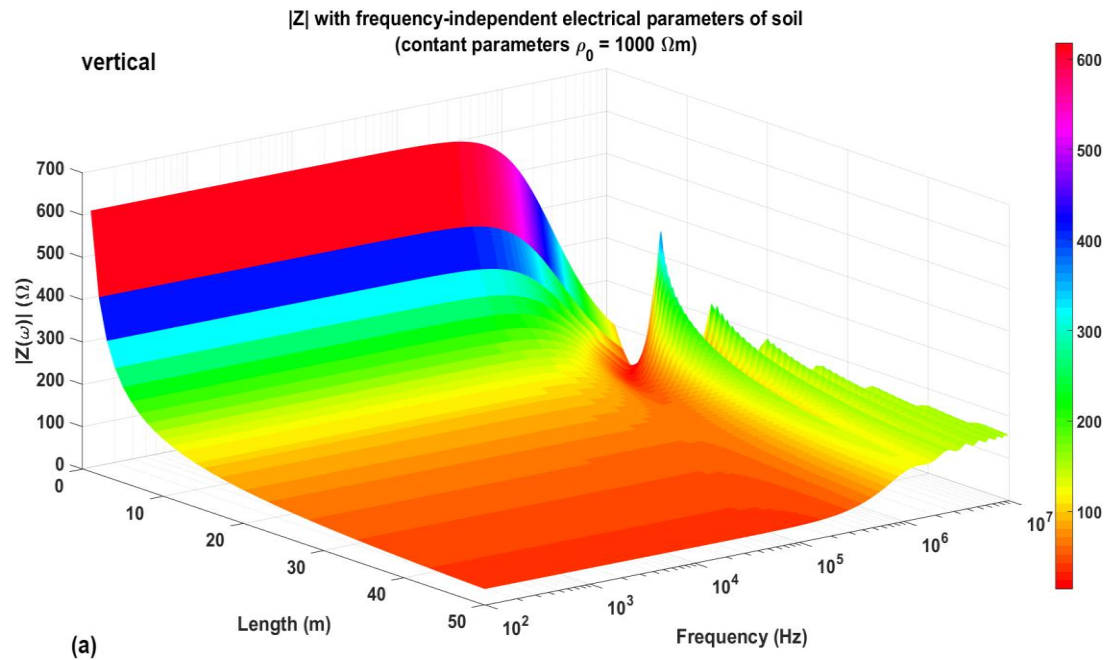
Primeiramente uma comparação entre a impedância de aterramento do eletrodo vertical é realizada.





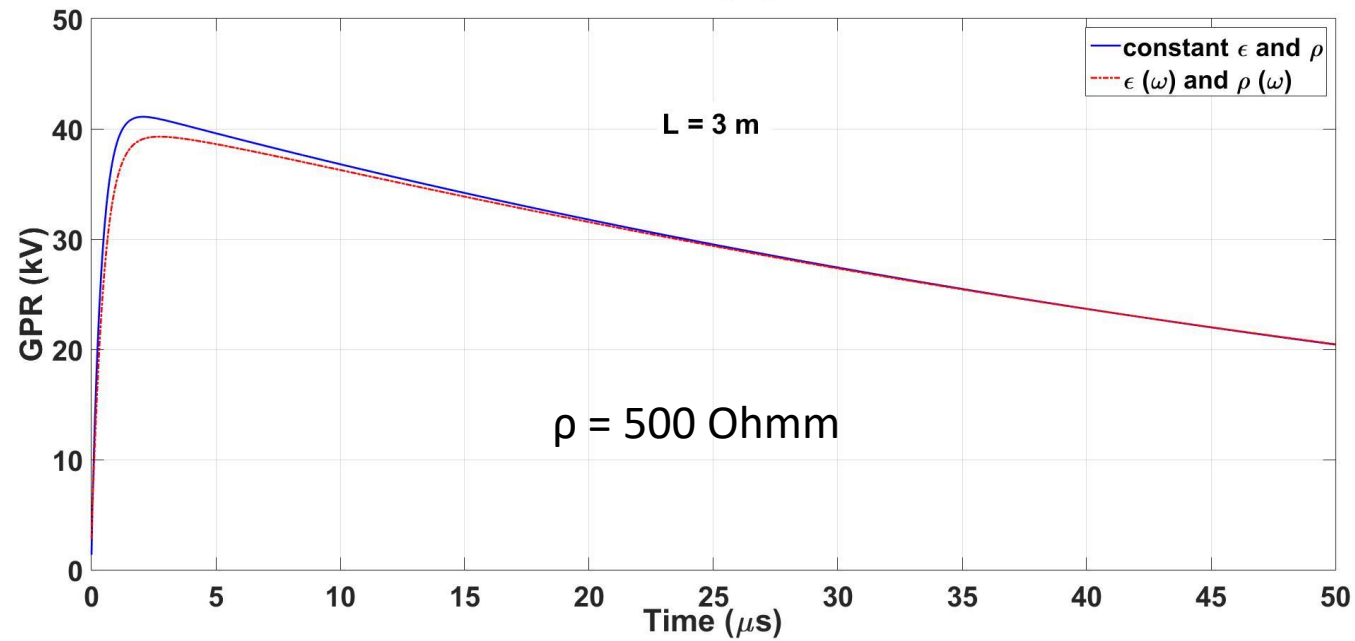
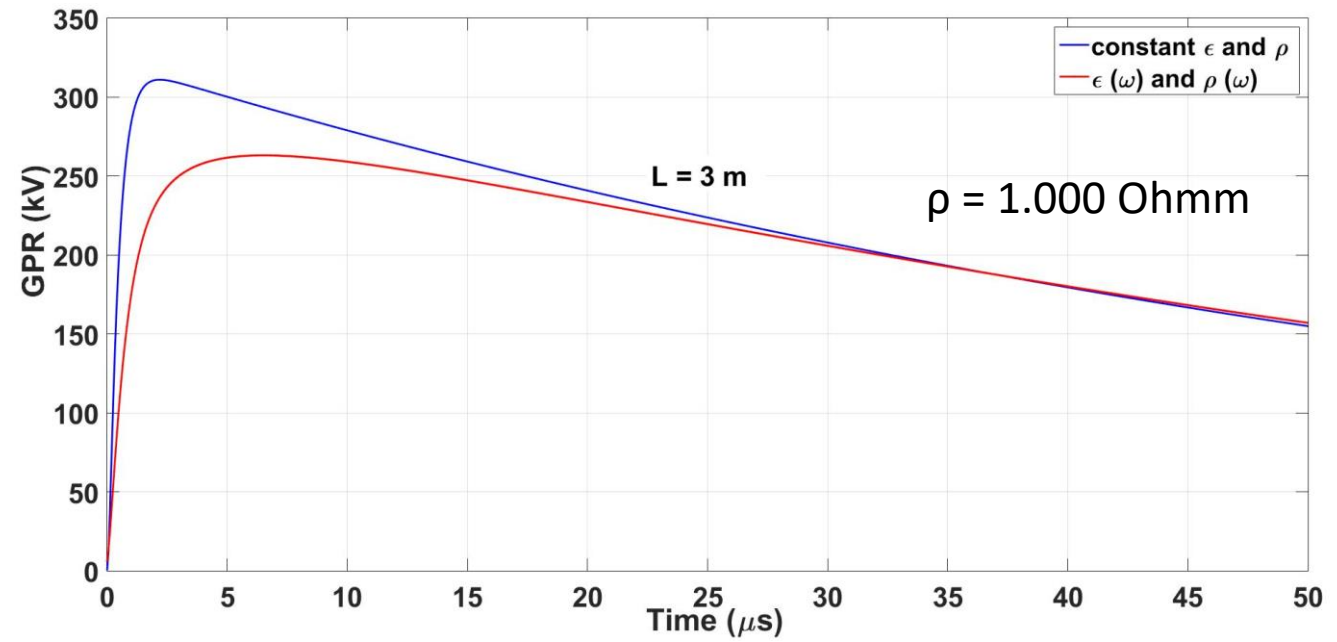
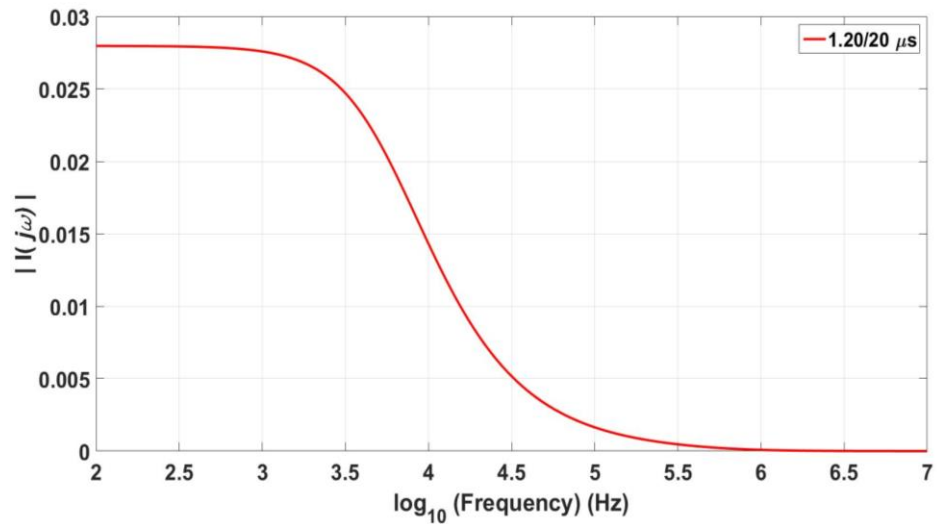
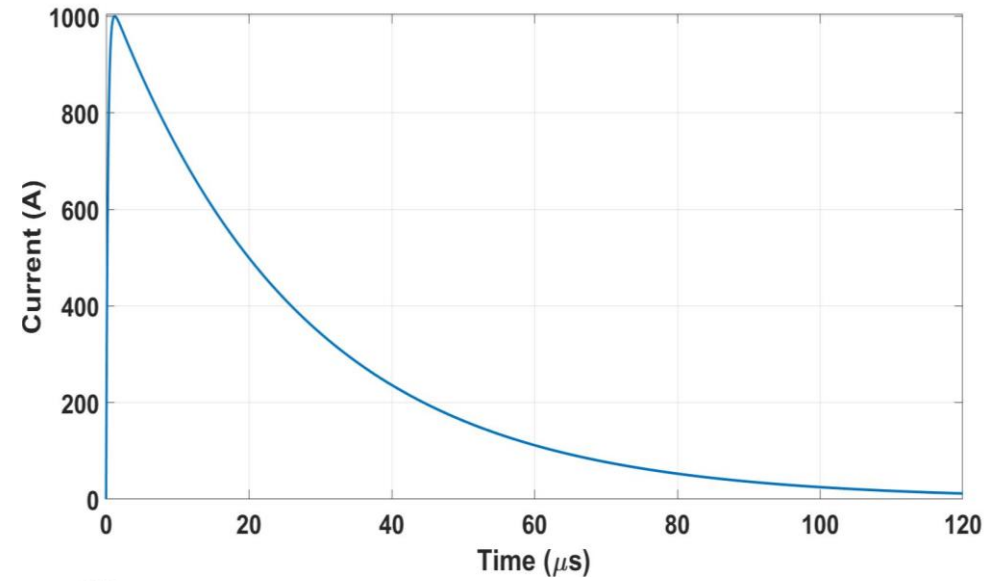


- ❖ Em baixas freq. ,a magnitude da impedância de aterramento é puramente resistiva para um intervalo inferior a 100 kHz. Acima de uma freq., denominada de freq. característica, a impedância do eletrodo pode assumir comportamento capacitivo ou indutivo, dependendo do intervalo da freq.
- ❖ Na maioria dos estudos TEM, considera-se que a impedância de aterramento é apenas uma resistência (concentrada) na qual é uma aproximação válida para baixas frequências.
- ❖ Entretanto, observa-se que quando a dependência da freq. nos parâmetros do solo é considerada, as frequências características são menores. A Magnitude e a fase são significativamente alteradas quando esse efeito é levado em consideração;
- ❖ Quanto maior a resistividade “DC” do solo (resistividade medida a 100 Hz), maior é a variação na magnitude da impedância na frequência. Tal comportamento impactará as tensões do GPR no domínio do tempo, conforme mostrada a seguir.



GPR

$$V(t) = L^{-1}\{Z(s)I(s)\} = GPR$$

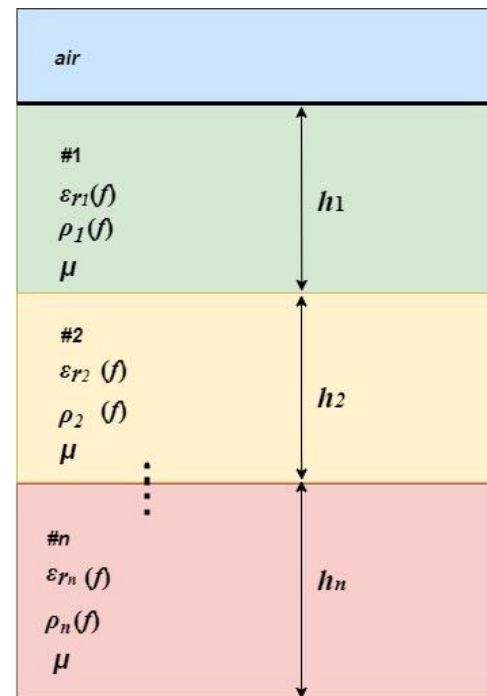


Solos estratificados

- Composição do solo;
- TLM por quadripolos;
- Impedância de aterramento em solos estratificados;
- GPR em solos estratificados;

Solo é composto por uma composição complexa de matéria orgânica e minerais compactado em camadas; Em termos de propriedade eletromagnéticas, o solo pode ser caracterizado por sua: resistividade (ρ), permissividade (ϵ) e permeabilidade (μ);

A permeabilidade (μ) é praticamente constante, sendo equivalente à do vácuo ($\mu \approx \mu_0$). Entretanto, a resistividade (ρ) e a permissividade (ϵ) são significativamente afetadas por fatores ambientais tais como a umidade, a temperatura, a salidade, assim como pela frequência do sinal transitório injetado ao eletrodo.

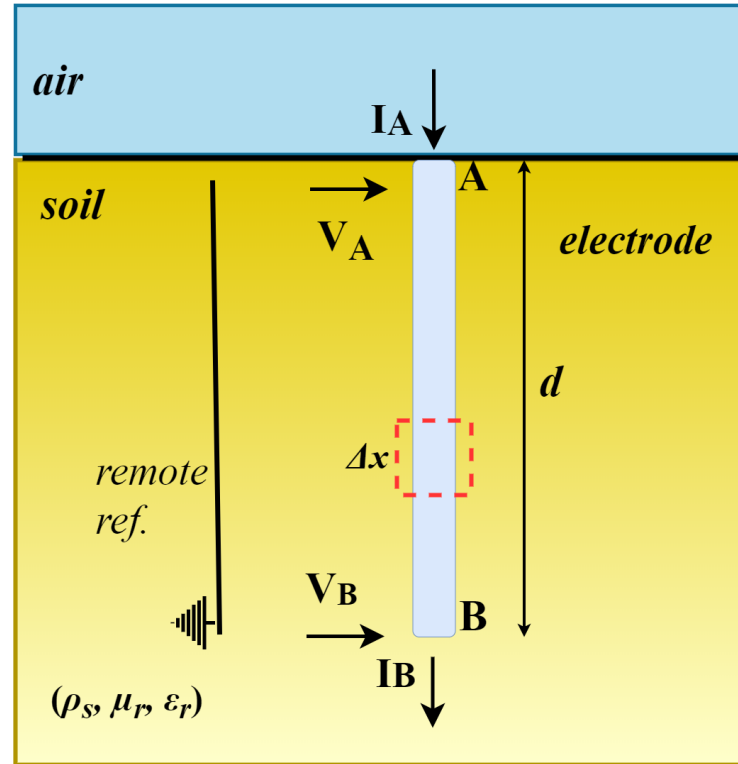


Equações da LT (Quadripolo)

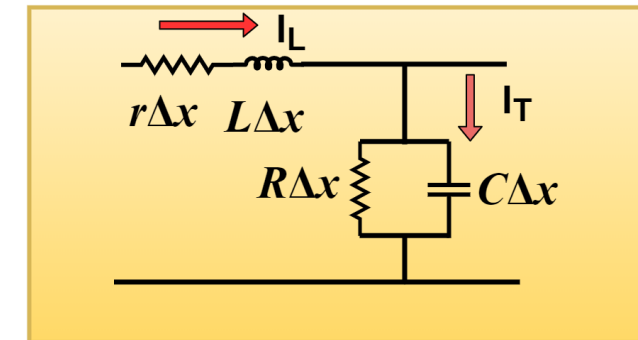
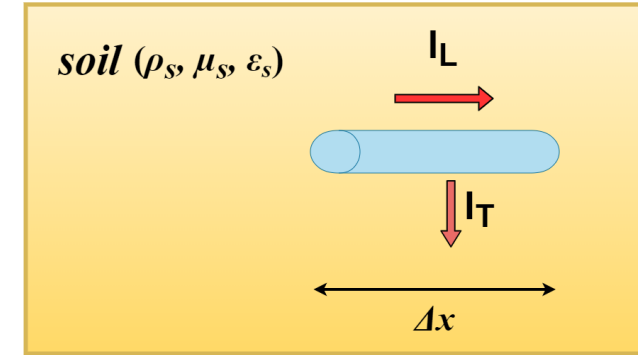
$$\begin{bmatrix} V_A(s) \\ I_A(s) \end{bmatrix} = \begin{bmatrix} \cosh(\gamma x) & Z_C \sinh(\gamma x) \\ Z_C^{-1} \sinh(\gamma x) & \cosh(\gamma x) \end{bmatrix} \begin{bmatrix} V_B(s) \\ I_B(s) \end{bmatrix}$$

$$Z_C(s) = \sqrt{(R_v + sL_v)(G_v + sC_v)^{-1}}$$

$$\gamma(s) = \sqrt{(R_v + sL_v)(G_v + sC_v)}$$



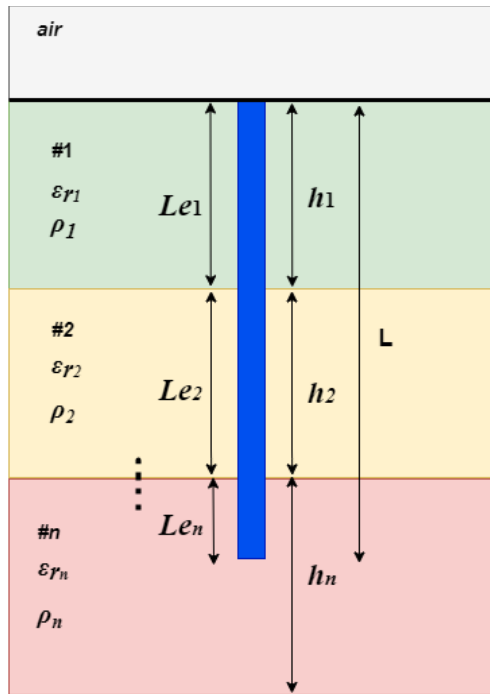
(a)



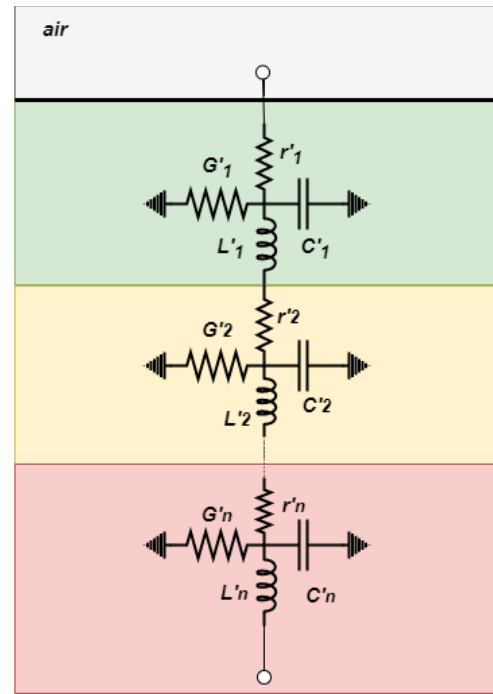
(c)

Modelo de Linha de Transmissão – Quadripolos em série

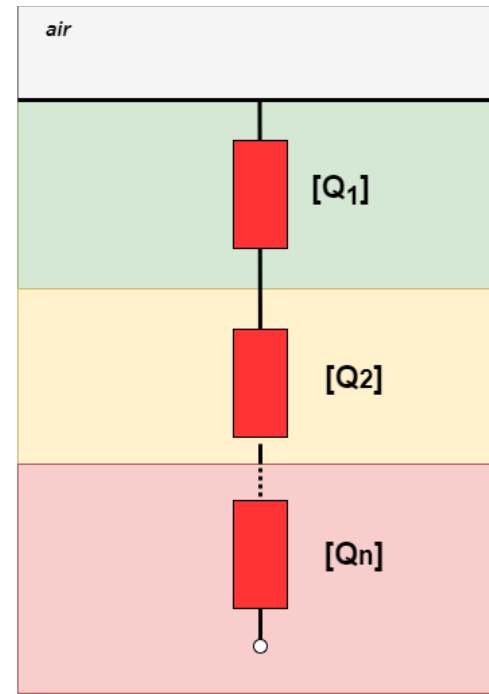
$$\begin{bmatrix} V_k(s) \\ I_k(s) \end{bmatrix} = \begin{bmatrix} A_i(s) & B_i(s) \\ C_i(s) & D_i(s) \end{bmatrix} \begin{bmatrix} V_m(s) \\ I_m(s) \end{bmatrix}$$



(a)



(b)



(c)

$$A_i(s) = D_i(s) = \cosh(\gamma_i(s) L_{ei})$$

$$B_i(s) = Z_{ci}(s) \sinh(\gamma_i(s) L_{ei})$$

$$C_i(s) = Z_{ci}^{-1} \sinh(\gamma_i(s) L_{ei})$$

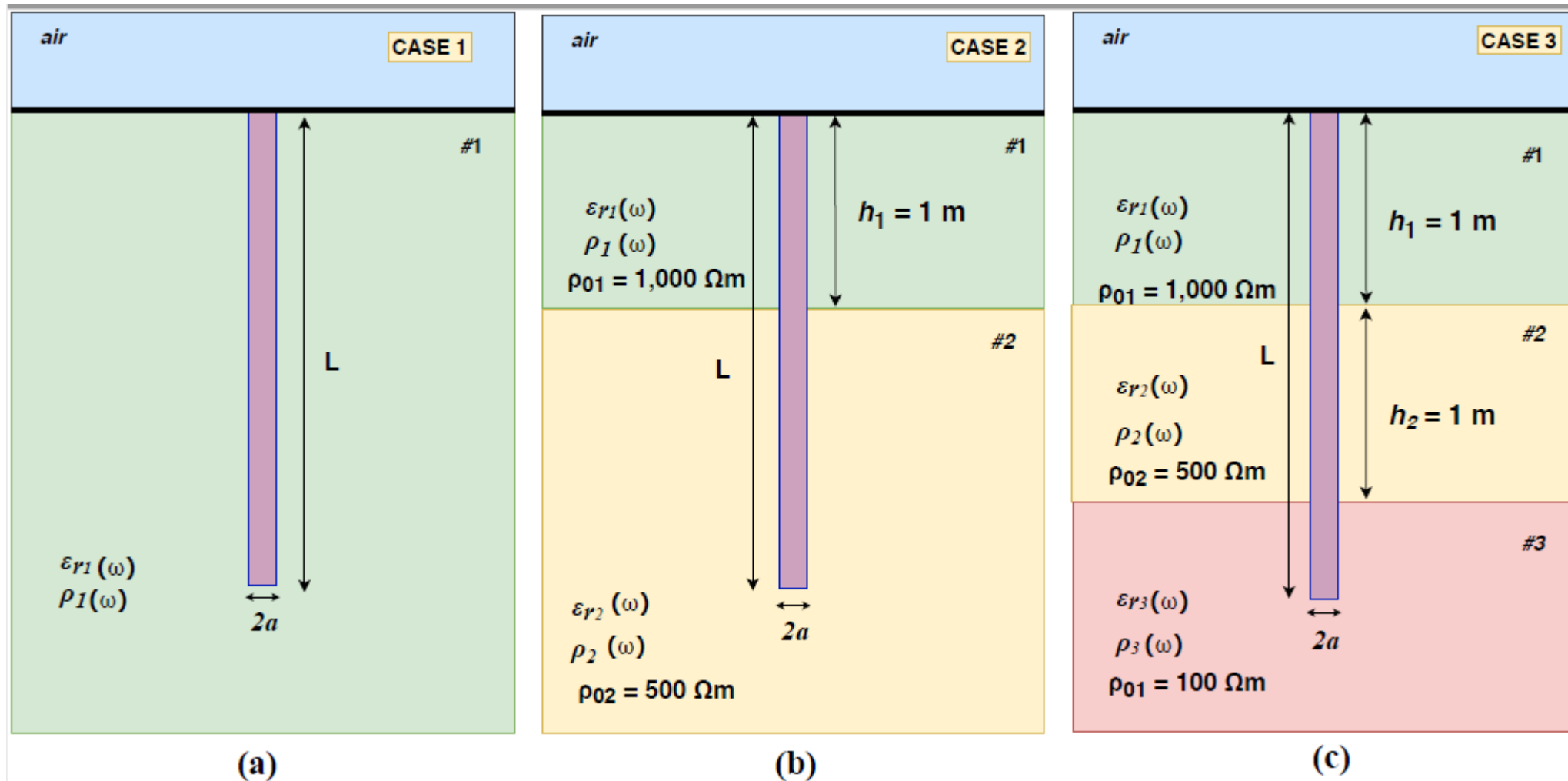
$$Z_{ci}(s) = \sqrt{(r'_i + sL'_i)(G'_i + sC'_i)^{-1}}$$

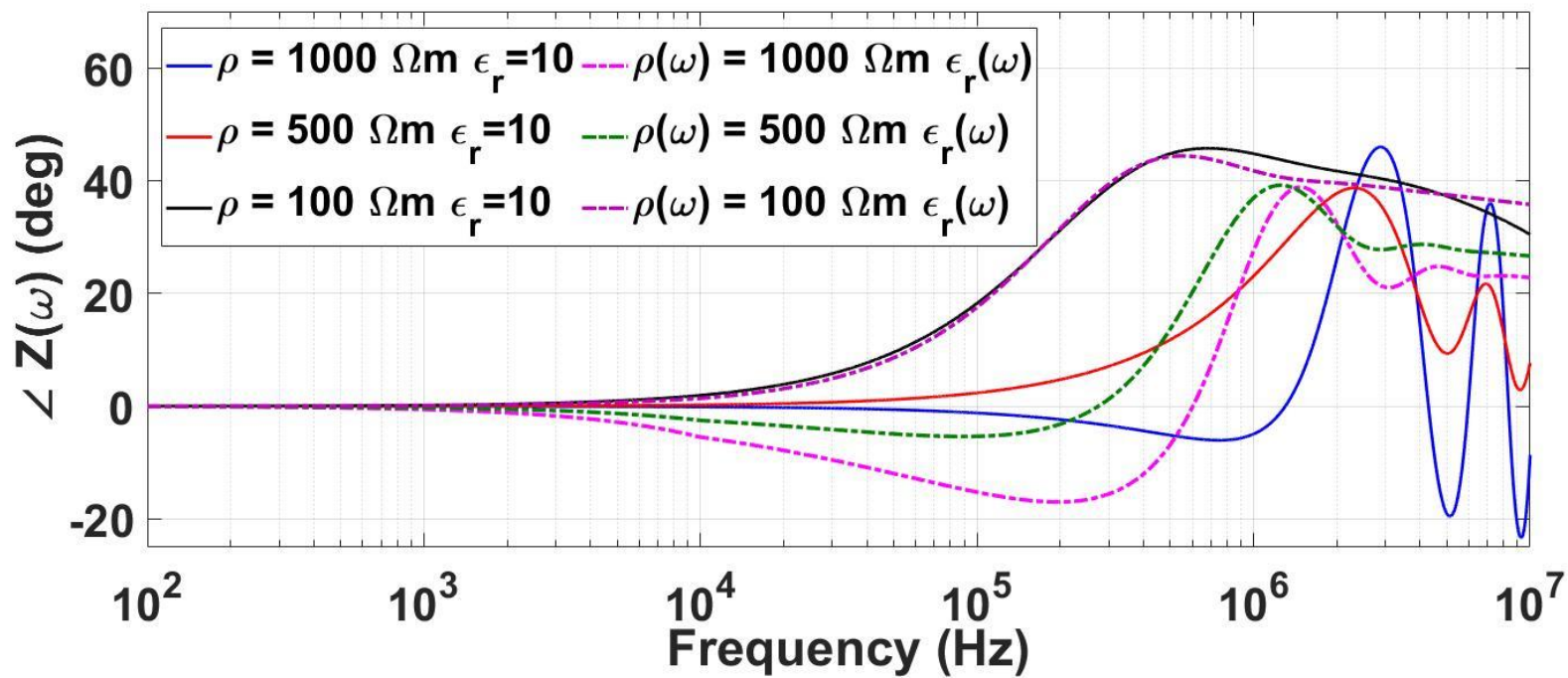
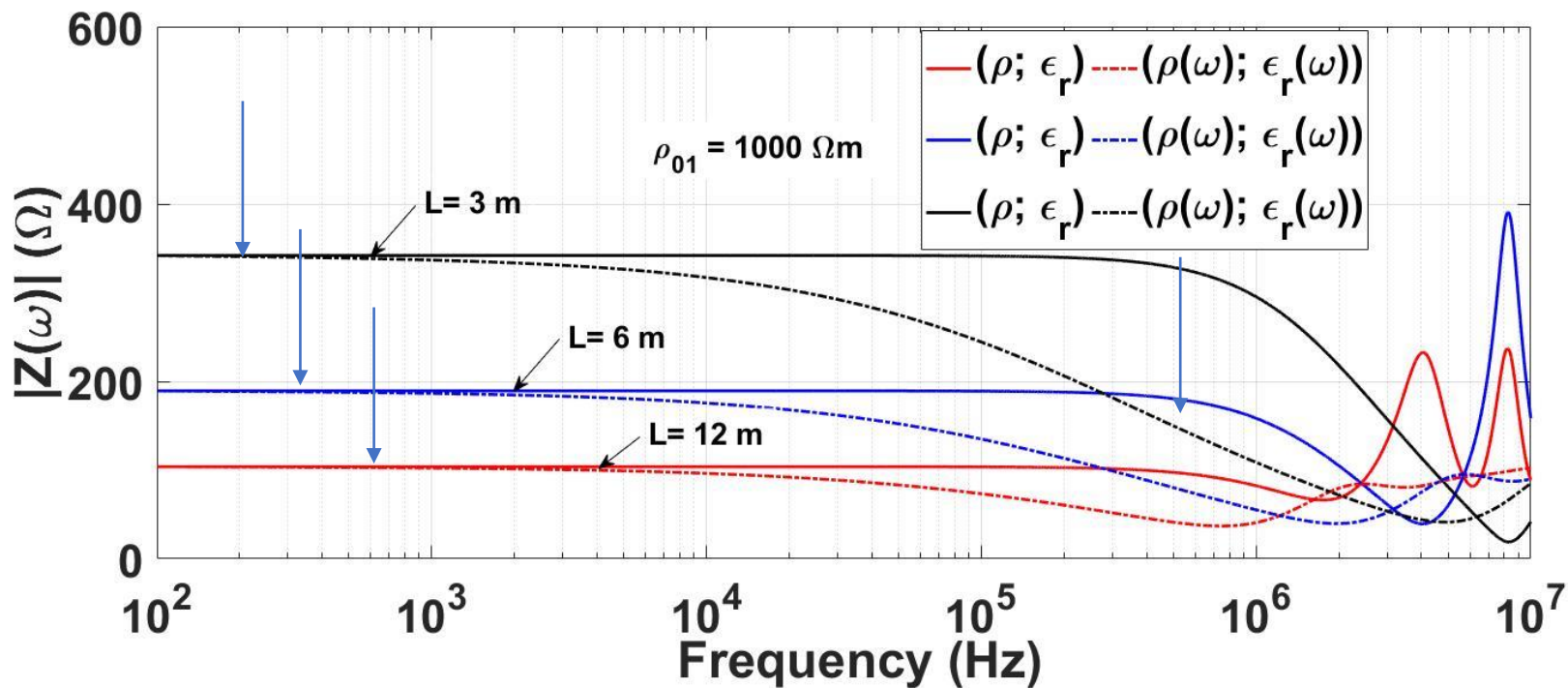
$$\gamma_i(s) = \sqrt{(r'_i + sL'_i)(G'_i + sC'_i)}$$

$$[Q_{eq}(s)] = [Q_1] \cdot [Q_2] \dots [Q_n] = \begin{bmatrix} A_{eq}(s) & B_{eq}(s) \\ C_{eq}(s) & D_{eq}(s) \end{bmatrix}$$

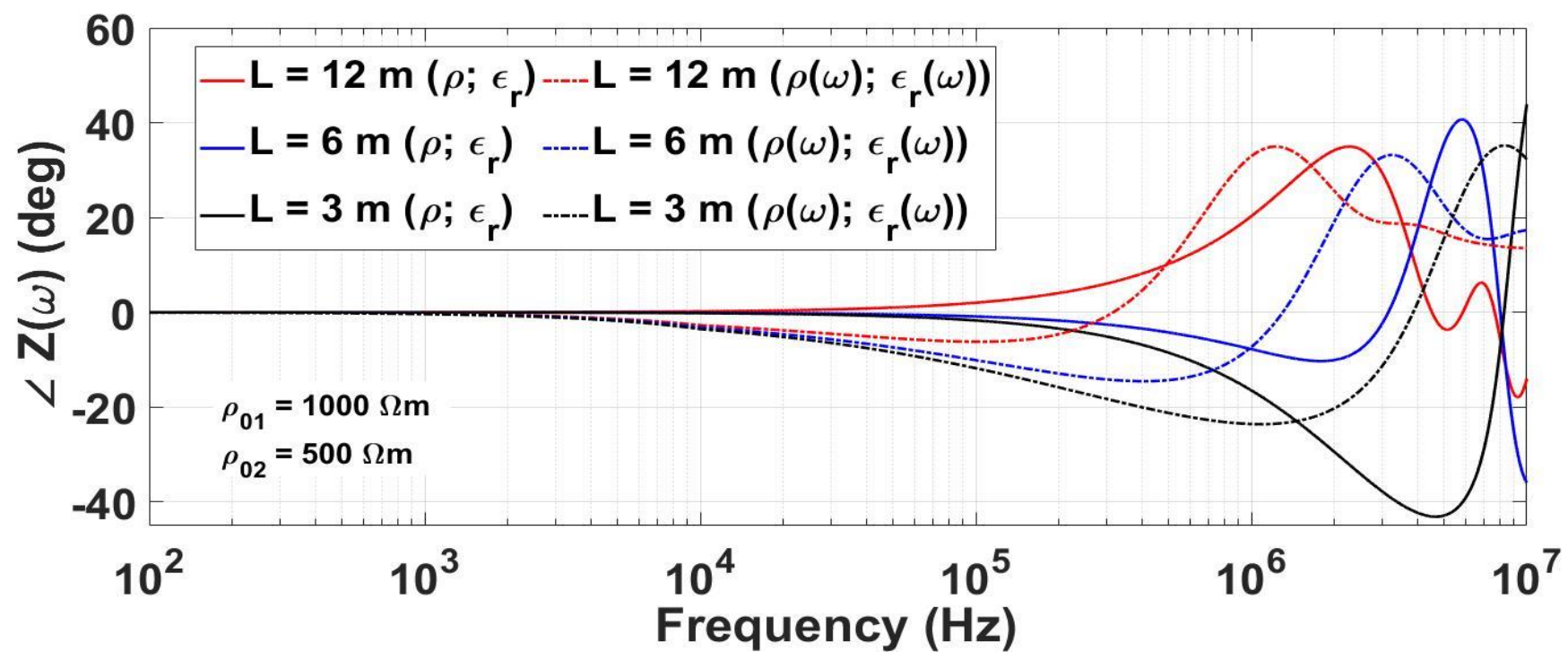
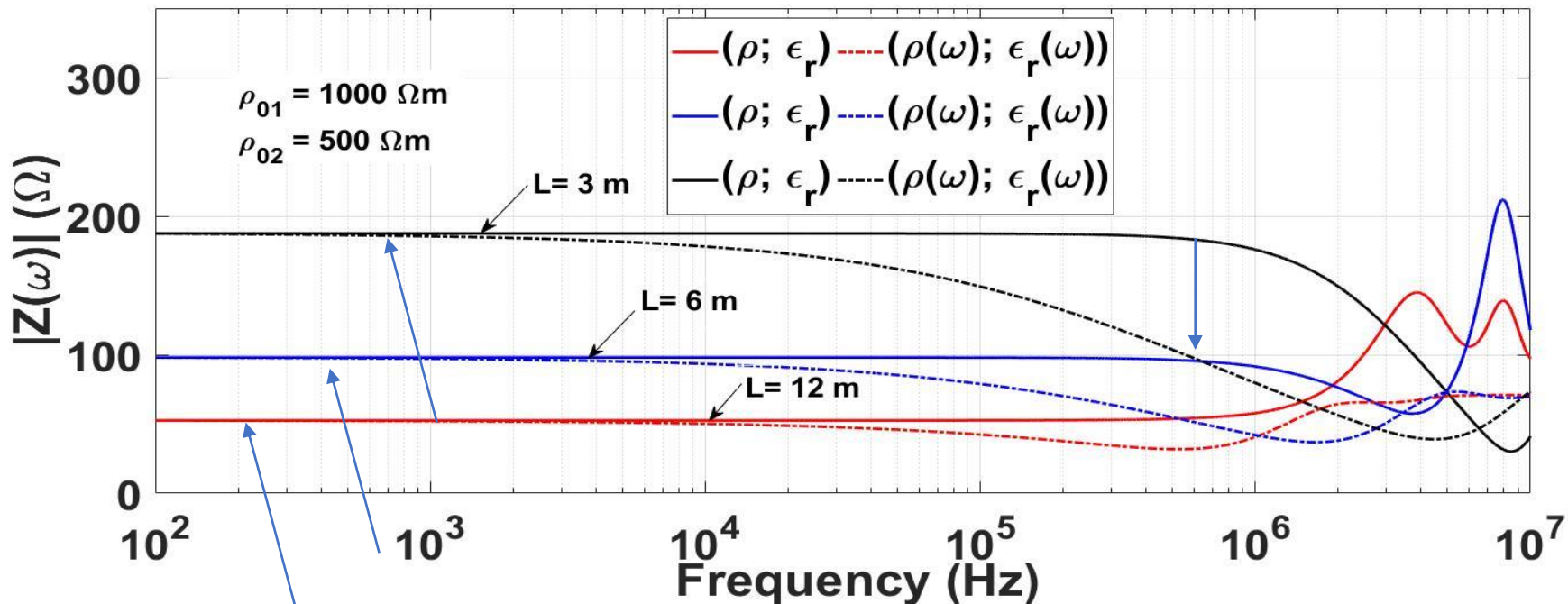
$$Z_{eq}(s) = \frac{A_{eq}(s)}{C_{eq}(s)} \Big|_{I_r(s)=0}$$

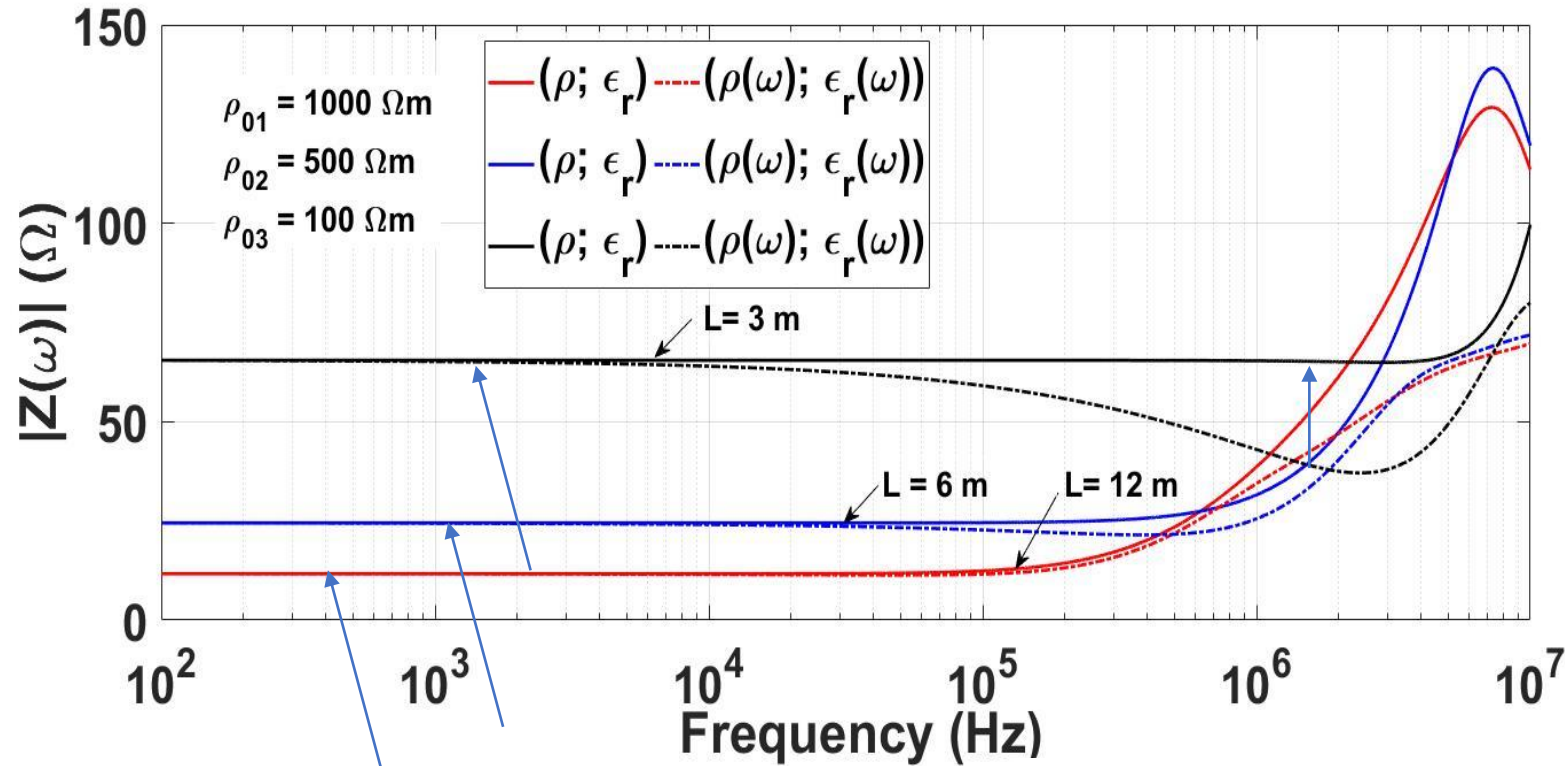
Vantagem do quadripolo- Considerar o efeito da frequência em cada camada e modelagem baseada nos parâmetros distribuídos do eletrodo (linha)





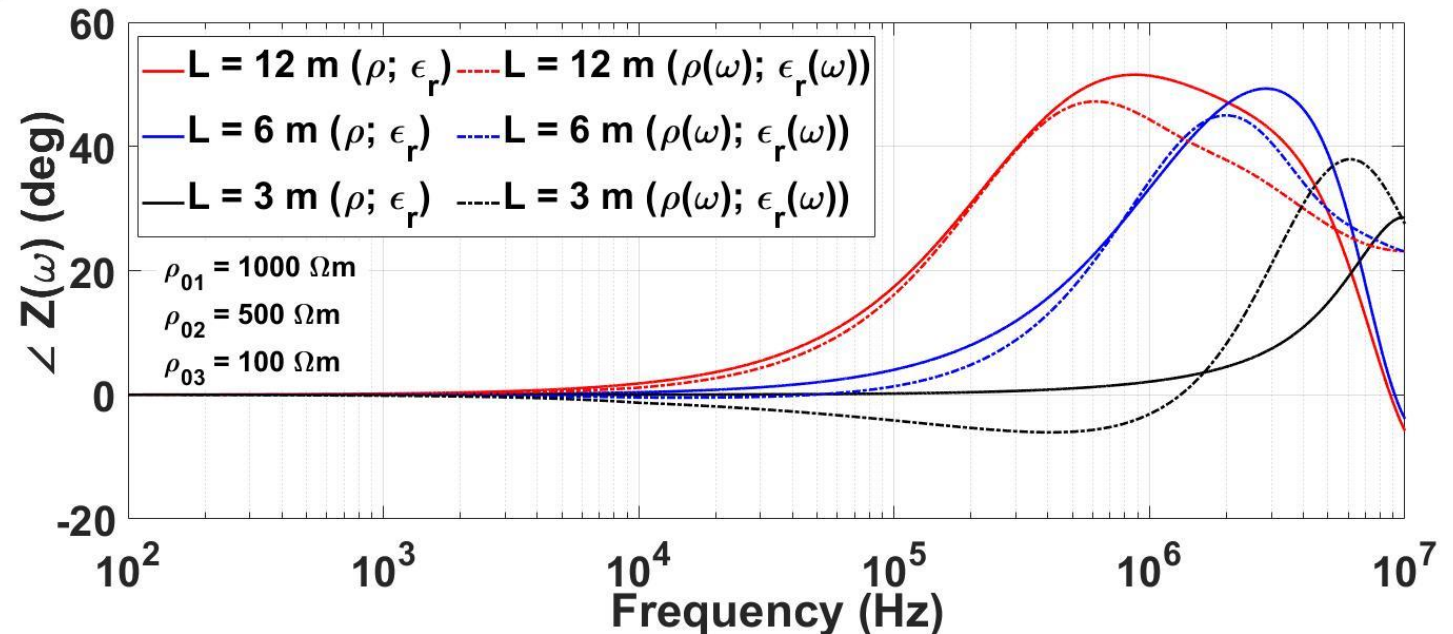
Case 2





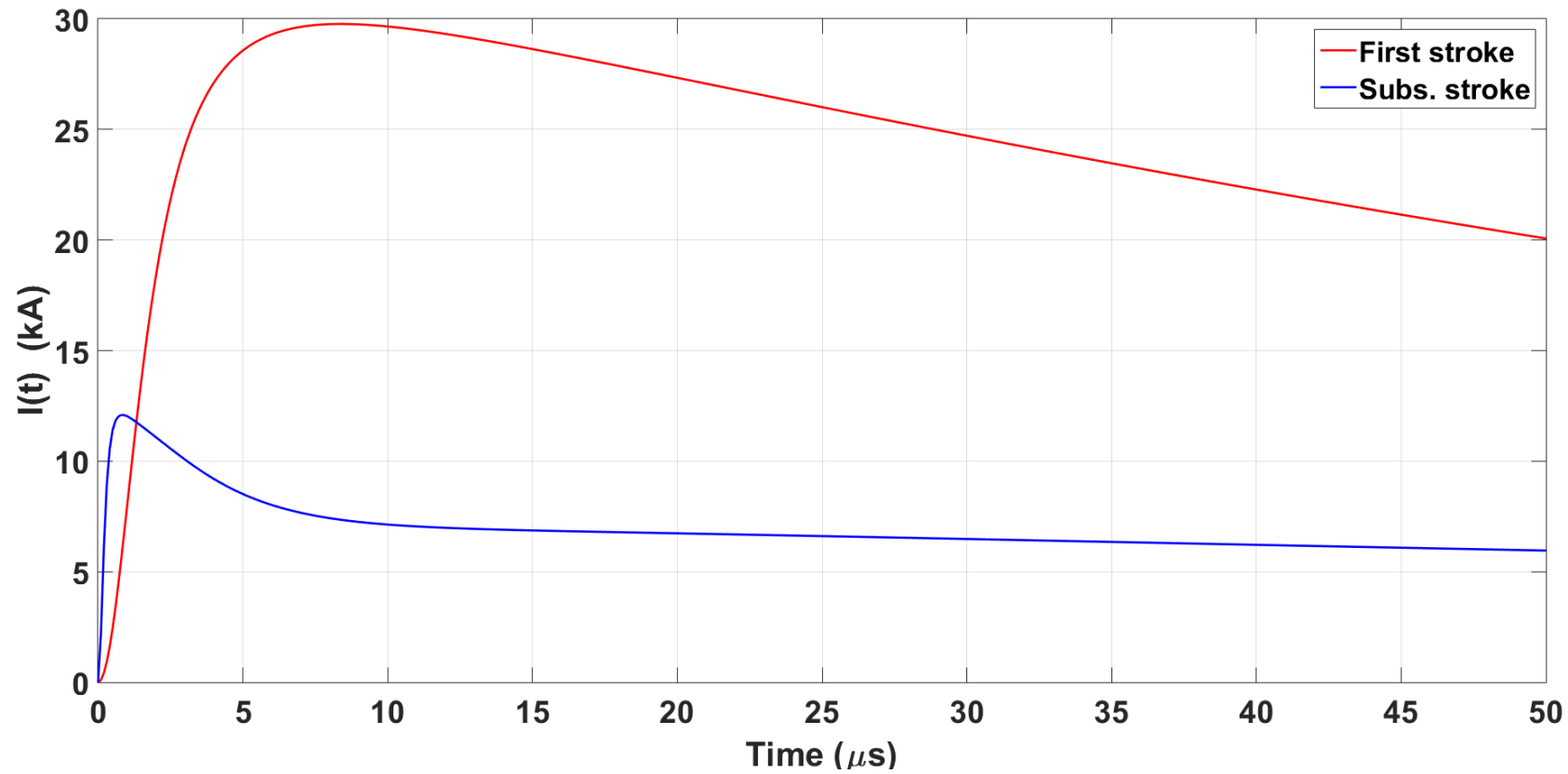
Case 3

A Resistência DC é menor quando maior o número de camadas; O efeito da freq. É menos pronunciado, quando aumentamos o número de camadas ou o comprimento do eletrodo.



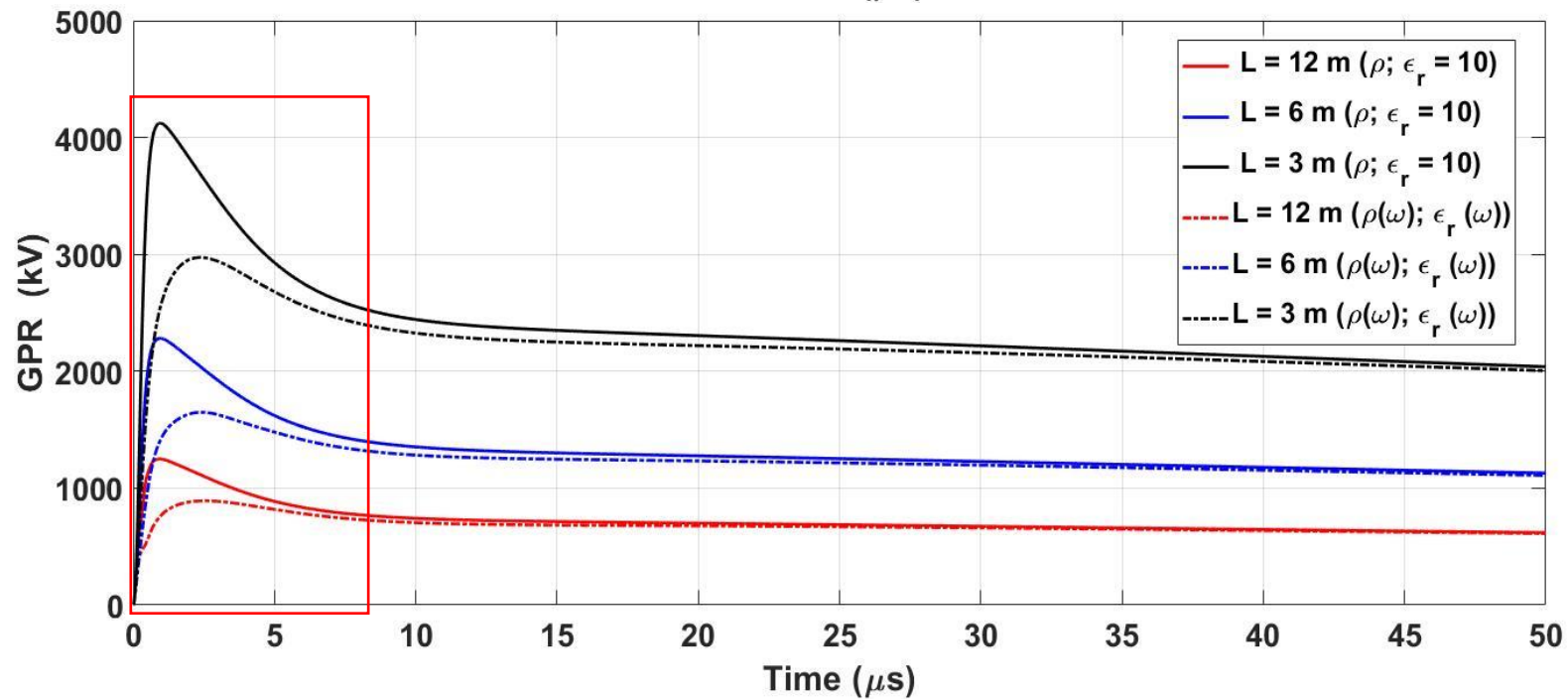
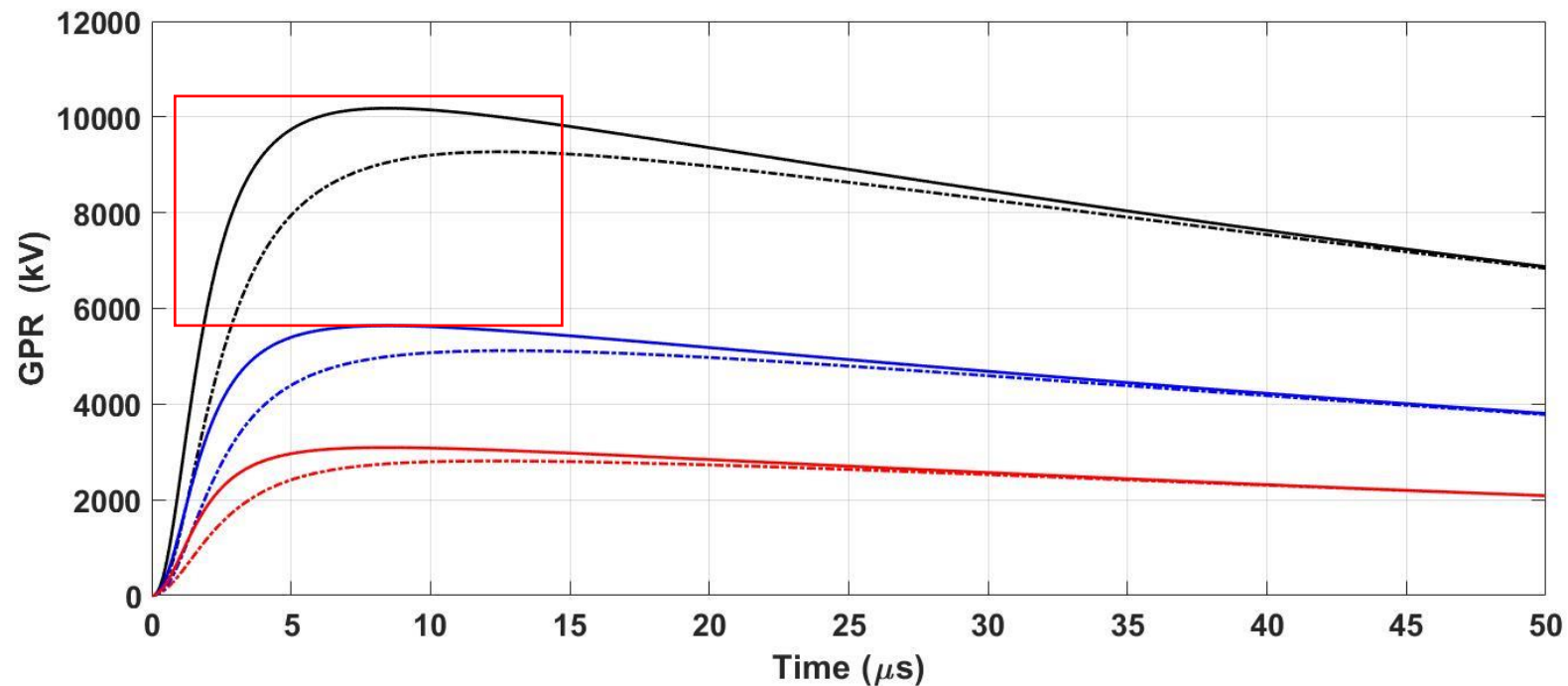
Cálculo do GPR para first e subsequente stroke

Parameters	I_0	τ_1	τ_2	n	I_0	τ_1	τ_2	n
First stroke	28	1.8	95	2	--	--	--	--
Subsequent stroke	10.7	0.25	2.5	2	6.5	2	230	2



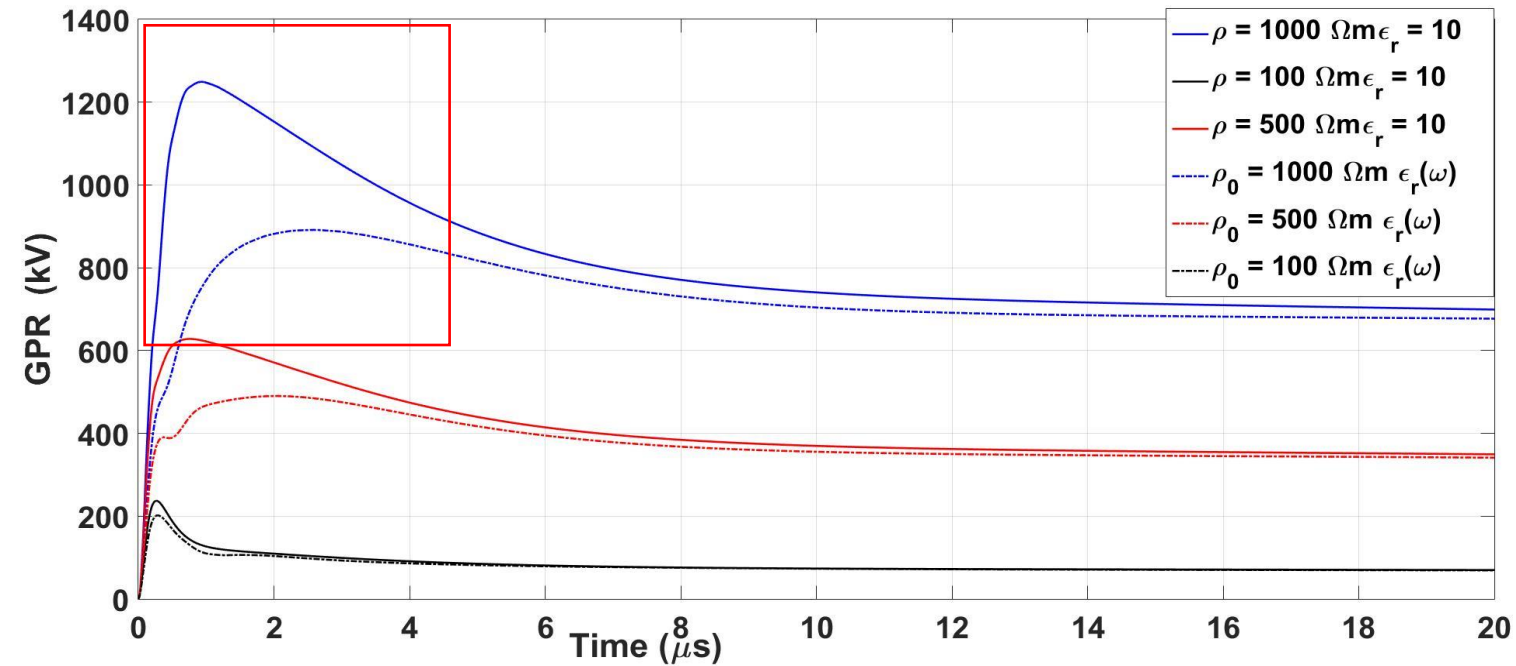
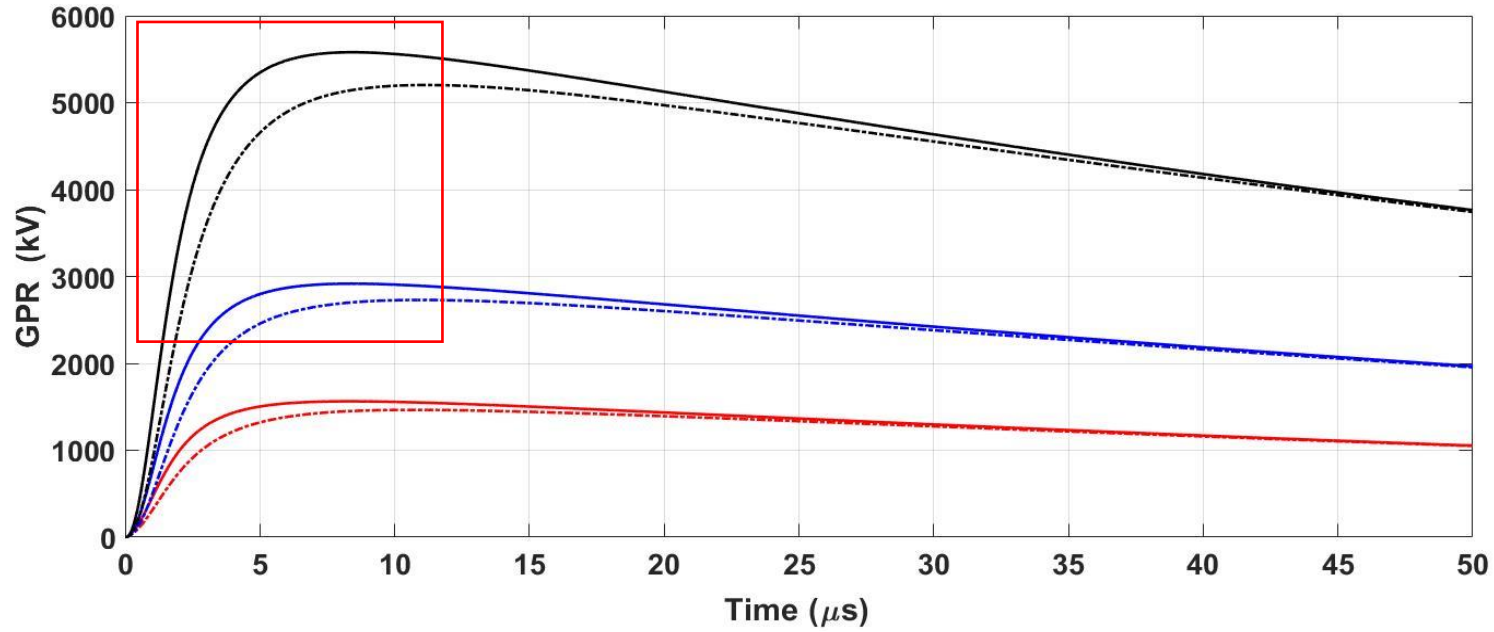
Case 1

$\rho = 1000 \Omega\text{m}$



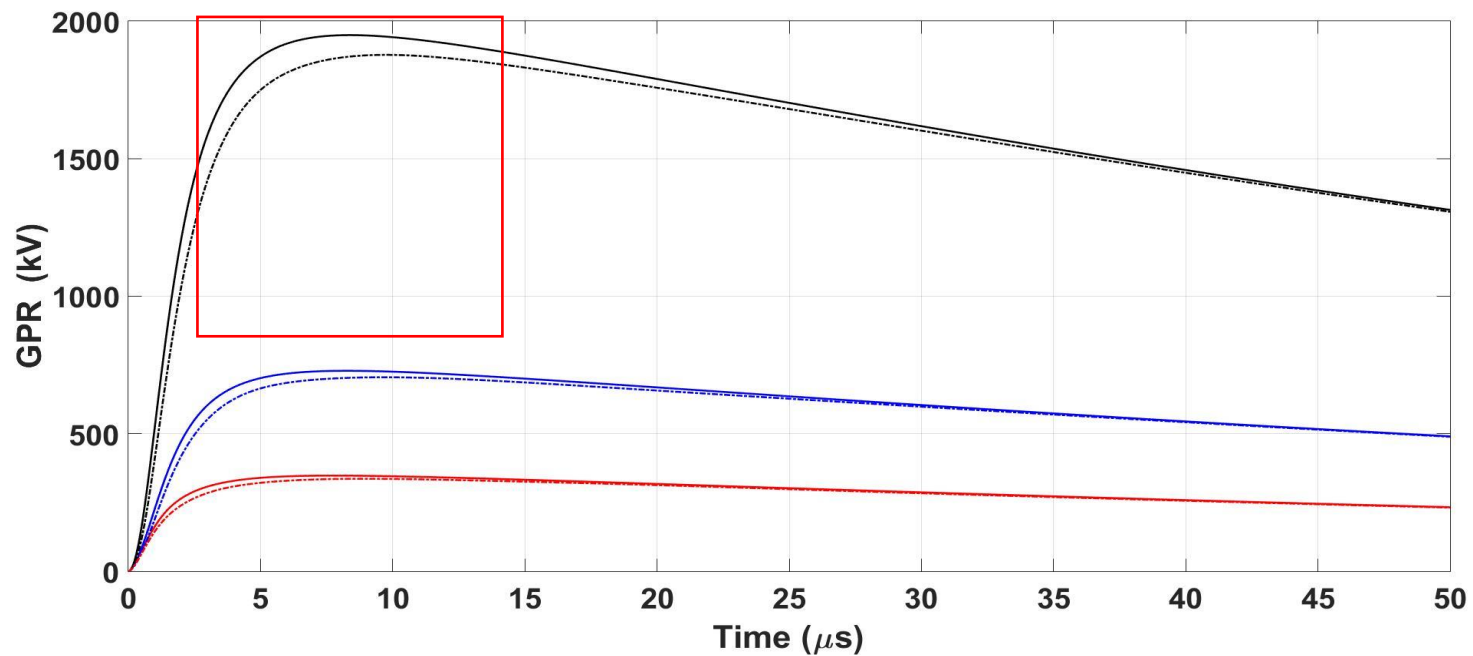
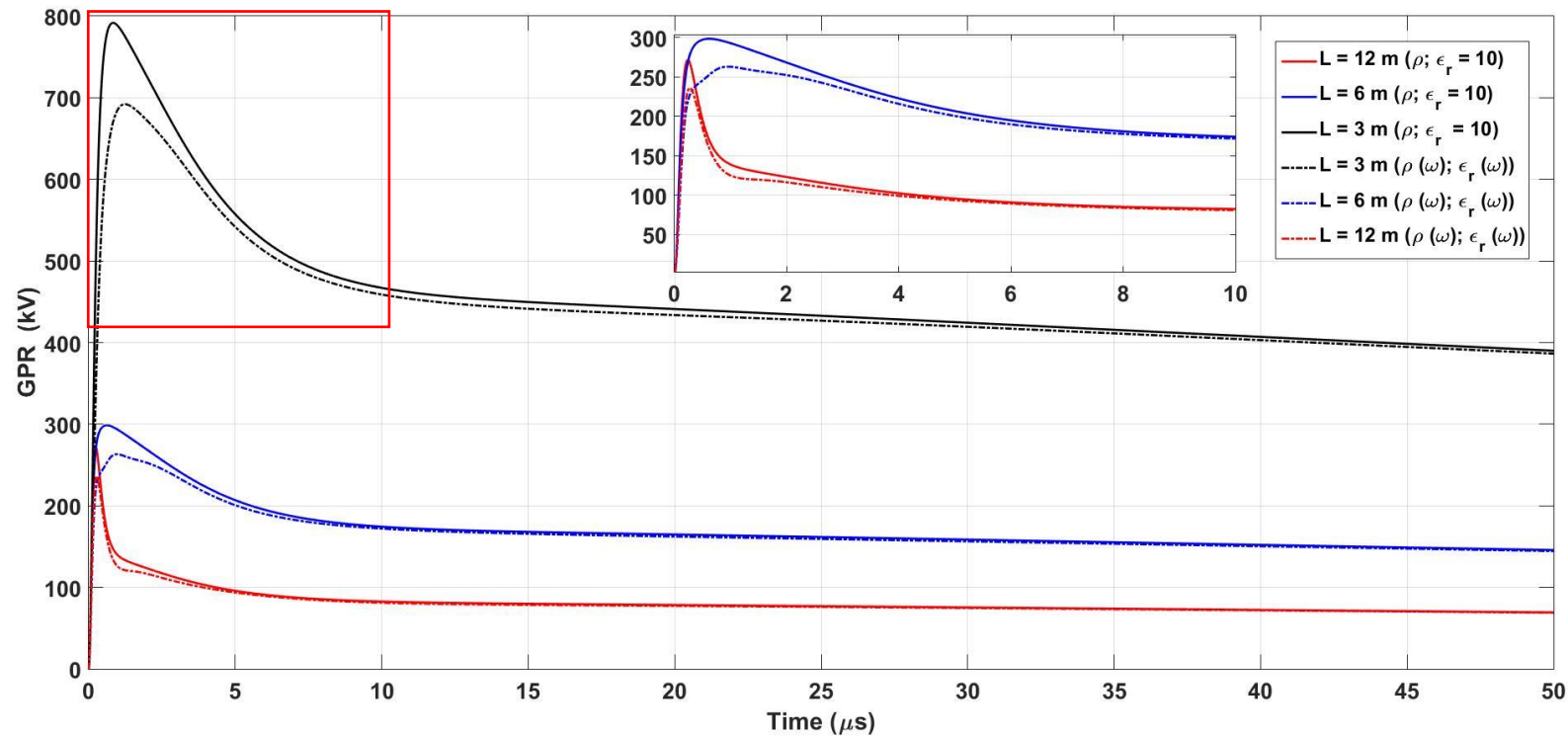
Case 2

$\rho = 1000/500 \text{ } \Omega\text{m}$



Case 3

$\rho = 1000/500/100 \text{ } \Omega\text{m}$



Comparação com Valores de pico do GPR

$$\alpha = \frac{V_{p(\omega)}}{V_{p(c)}}$$

Observa-se que quando mais camadas do solo são consideradas, e first strokes, o efeito da freq. nos parâmetros do solo é menos influenciado.

Entretanto, para subsequente strokes (ondas mais rápidas), as amplitudes reduzidas significativamente, especialmente para solos de uma camada.

TABLE II
VOLTAGE PEAKS (KV) AND RATIO α FOR CASE 1.

Length	First Stroke			Subsequent Stroke		
	$V_p(\omega)$	$V_p(c)$	α	$V_p(\omega)$	$V_p(c)$	α
L = 3 m	9,300	10,800	0.861	2,970	4,120	0.721
L = 6 m	5,120	5,640	0.908	1,650	2,280	0.723
L = 12 m	2,810	3,090	0.909	890	1,250	0.713

TABLE III
VOLTAGE PEAKS (KV) AND RATIO α FOR CASE 2.

Length	First Stroke			Subsequent Stroke		
	$V_p(\omega)$	$V_p(c)$	α	$V_p(\omega)$	$V_p(c)$	α
L = 3 m	5,200	5,580	0.931	1,760	2,260	0.779
L = 6 m	2,720	2,900	0.938	930	1,190	0.781
L = 12 m	1,460	1,560	0.936	500	635	0.787

TABLE IV
VOLTAGE PEAKS (KV) AND RATIO α FOR CASE 3.

Length	First Stroke			Subsequent Stroke		
	$V_P(\omega)$	$V_P(c)$	α	$V_P(\omega)$	$V_P(c)$	α
L = 3 m	1,880	1,950	0.964	690	790	0.873
L = 6 m	705	730	0.966	260	300	0.867
L = 12 m	335	345	0.971	235	270	0.870

Conclusões

- Métodos numéricos são amplamente empregados para calcular a impedância de aterramento, no qual são usados como referência;
- Verifica-se que para uma análise precisa de transitórios eletromagnéticos deve-se considerar a dependência da freq. Nos parâmetros do solo para calcular a impedância dos eletrodos e GPRS.
- Solos estratificados resultam em uma resistividade menor, e o efeito da freq. Torna-se menos significativo nesses casos.

Aula 3

- Ionização do solo
 - Modelo a parâmetros concentrados-eletrodos
 - Malhas de Aterramento
- (Exercício)