

# IT308 - Tópicos em Técnicas de Alta Tensão II

## Aterramento no Sistema Elétrico Aula-03

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# Tópicos

- Ionização do Solo;
- Comparação de Modelos;
- Vector Fitting;
- Modelos a parâmetros concentrados;
- Aproximação pela teoria eletromagnética;
- Malhas de Aterramento;

# Ionização do solo

## The Transmission Line Modeling Method to Represent the Soil Ionization Phenomenon in Grounding Systems

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### II. SOIL IONIZATION OVERVIEW

During the process of current dissipation through the grounding system, if the voltage in the electrodes is high enough with consequent generation of an electric field exceeding a given threshold—critical electric field, the rupture of the soil dielectric around the electrodes up to a certain radial distance may occur. This region, referred to as ionized, can be

interpreted as a type of irregular conductivity wrapped around the grounding conductors [5]. This process culminates in a reduction of electrical resistivity in the ionized region. This phenomenon can be interpreted as if the electrode assumed a larger diameter than its original value.

The implementation of a mathematical model representing the soil disruption can be idealized considering the variation of soil resistivity and/or the increase of the electrode diameter. Studies have shown that in fact the only soil property that is affected in the ionization process is the resistivity. The electric permittivity and magnetic permeability are not significantly changed and the practical effect of the soil disruption is the reduction of the generated earth potential [5].

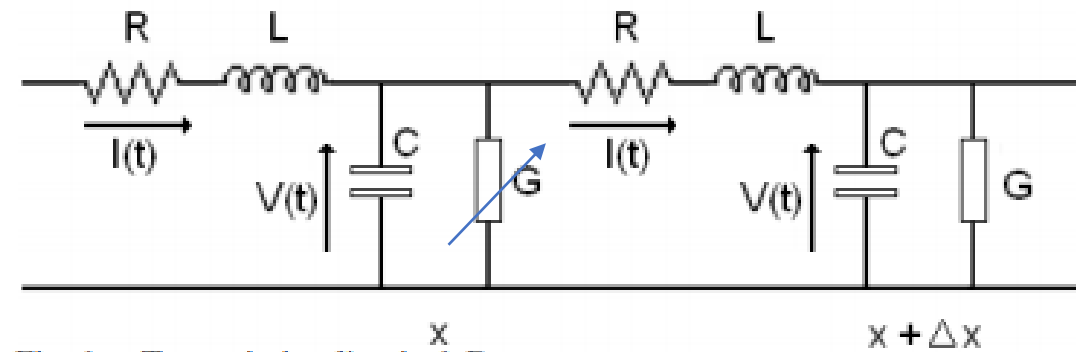
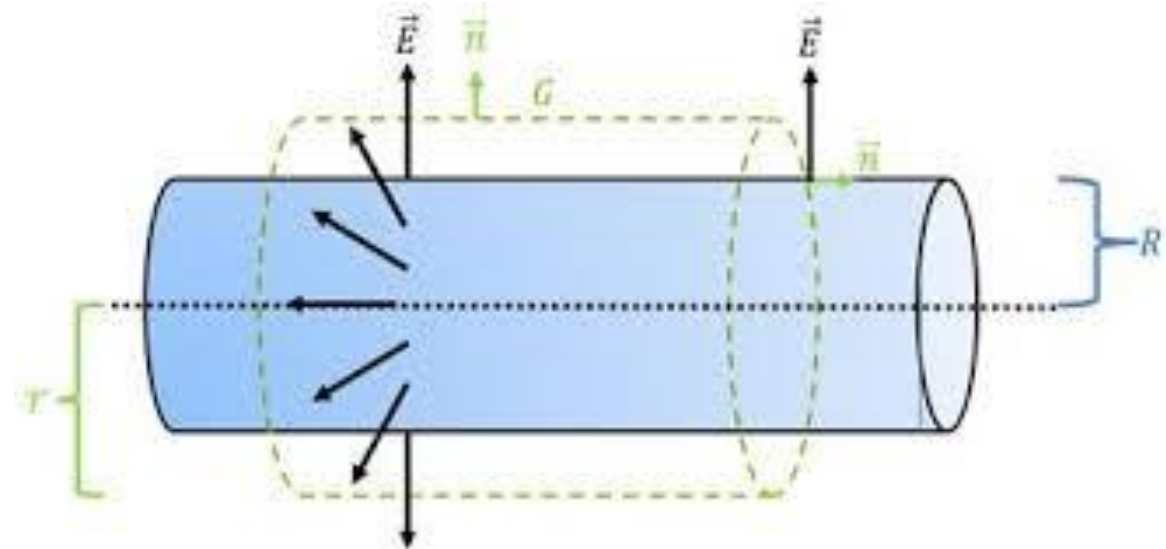


Fig. 1. Transmission line in I-D.



# Fatores

In brief Soil Ionization effect depends on:

- Water Content
- Soil Resistivity (Type)
- Temperature
- Grain Size
- Soil Compaction
- Electric Field Strength
- Grounding System Dimension
- Electrode Length

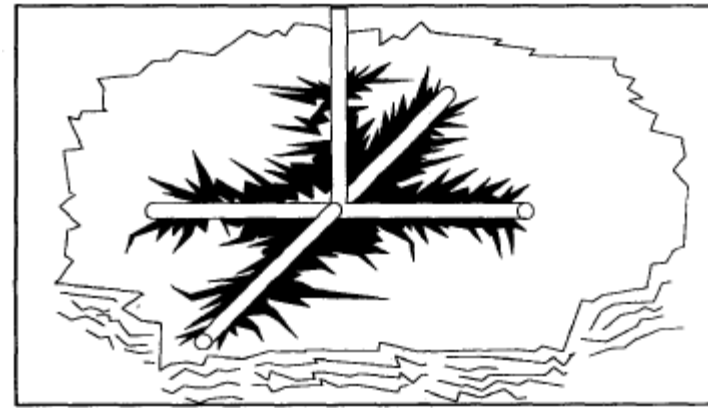
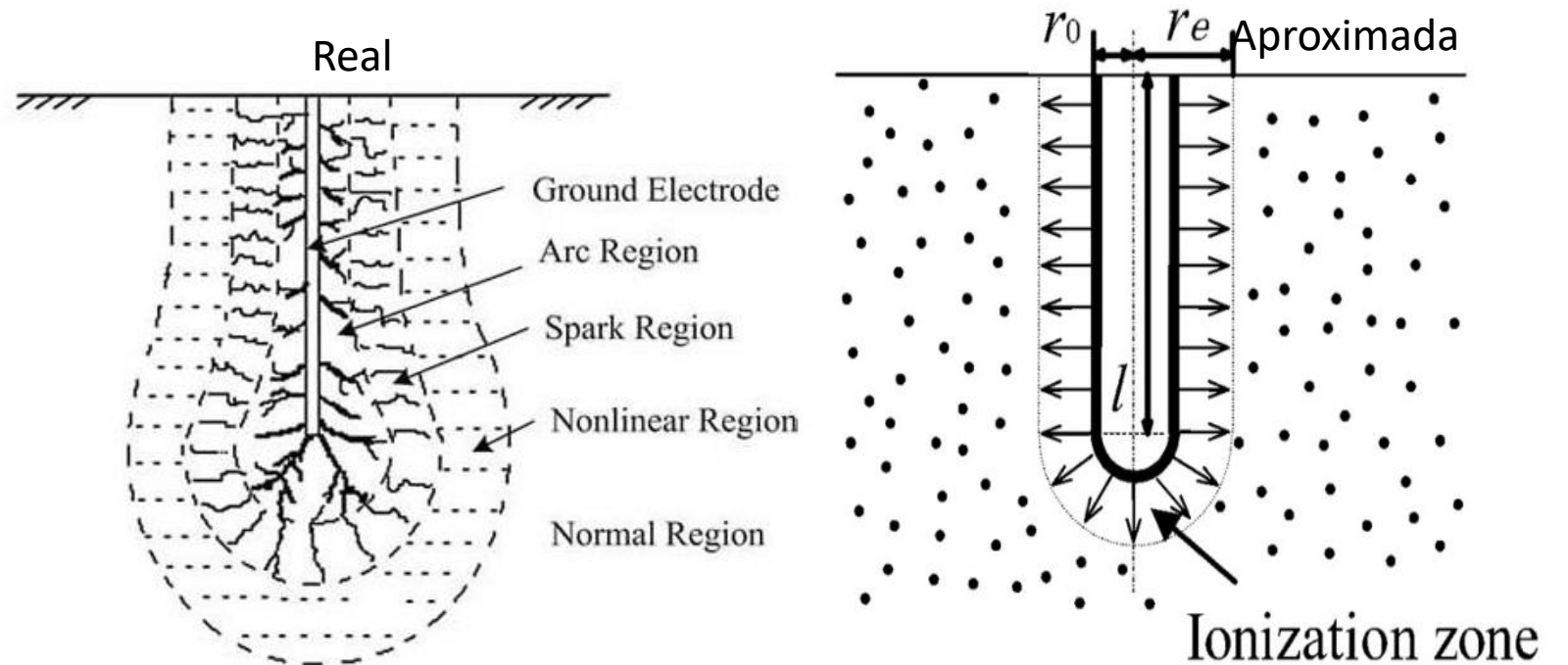


Fig. 1. Soil breakdown near the current admitting point of a grounding system.



If the critical electric field is exceeded, an increase in the effective radius of the conductor around the ionized region is established. Based on the transmission line representation, this increase in the diameter implies the need for a change in the line parameters per unit length with consequent alteration of the circuit elements present in the model [6], [7]. In this approach, the model is composed of a set of small sections (segments), with lumped components as shown in Fig. 1.

The soil disruption is considered uniform around the ionized region, represented by the area corresponding to the increase in the radius of the electrode, as shown in Fig. 2.

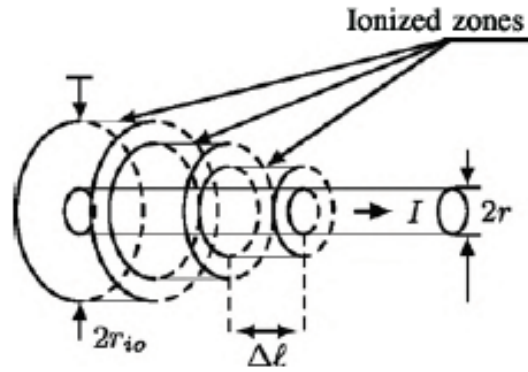


Fig. 3. Ionisation zone of a buried grounding electrode

The current density, at the critical value  $E_c$  of soil ionisation, on the boundary of ionized zone is [2]:

$$J_{io} = \frac{E_c}{\rho} = \frac{I_{io}}{2\pi\Delta\ell r_{io}} \quad (7)$$

and the equivalent radius for each segment is obtained by [2]:

$$r_{io} = \frac{I_{io}}{E_c} \frac{\rho}{2\pi\Delta\ell} \quad (8)$$

surface to the earth easier. The critical breakdown strength  $E_{crit}$  of the surrounding soil can be obtained from the following formula [17]:

$$E_{crit} = 241 \cdot \sigma_E^{-0.215} \quad (15)$$

where  $E_{crit}$  is in kilovolts per meter and  $\sigma_E$  is in  $(\Omega m)^{-1}$ .

It should be remarked that we used for this analysis a constant value for  $e_{crit \text{ soil}}$  during the computed time window and for all electrodes, namely equal to 300 kV/m, which is recommended in many technical papers for general purposes [8]. For comparison, we also analyzed this example employing  $e_{crit \text{ soil}}$  equal

$E(x) = \rho J(x)$  → Densidade de corrente em uma dada área

$|J(x)| = \frac{I}{A}$  → Corrente transversal que 'atravessa' uma dada área

# Procedimento para o cálculo do GPR

To this purpose, the current density is defined as the current  $I$  flowing through the area of a segment associated with the node  $J$  at a given instant of time  $t$  in an iteration  $K$ , as given in (10) [7]

$$J_c(J, t) = \frac{I(J, t)}{2 \cdot \pi \cdot \Delta x \cdot a} \quad (10)$$

where  $J_c$  is the conductor current density ( $A/m^2$ ).

The electric field on a line segment represented by a node  $J$  can be established by using (11)

$$E(J, t) = \rho_s \cdot J_c(J, t). \quad (11)$$

In the second step, a verification is carried out for each node  $J$  so as to check whether the electric field  $E(J, t)$  exceeds the critical value of electric field  $E_{cr}$ . If so, the new values of  $G(J, t)$  obtained by (3) and (4) of a node  $J$  are recalculated representing the soil ionization along the associated segment. Otherwise, in the absence of ionization, the algorithm proceeds normally. In both cases, the  $R$ ,  $L$ , and  $C$  line parameters are determined by (5)–(9).

$$G(t) = \frac{2 \cdot \pi \cdot \Delta x}{\rho_s \cdot \left[ \ln \left( \frac{2 \cdot l}{\sqrt{2 \cdot h \cdot a}} \right) - 1 \right]} \cdot \sqrt{1 + \frac{I(t)}{I_g}} \quad L = \frac{\mu_0 \cdot \Delta x}{2 \cdot \pi} \cdot \left[ \ln \left( \frac{2 \cdot l}{\sqrt{2 \cdot h \cdot a}} \right) - 1 \right]$$

$$C = \frac{2 \cdot \pi \cdot \epsilon_0 \cdot \epsilon_r \cdot \Delta x}{\ln \left( \frac{2 \cdot l}{\sqrt{2 \cdot h \cdot a}} \right) - 1}$$

$$R = \frac{\rho_c \cdot \Delta x}{2 \cdot \pi \cdot a \cdot \delta}$$

Efeito skin

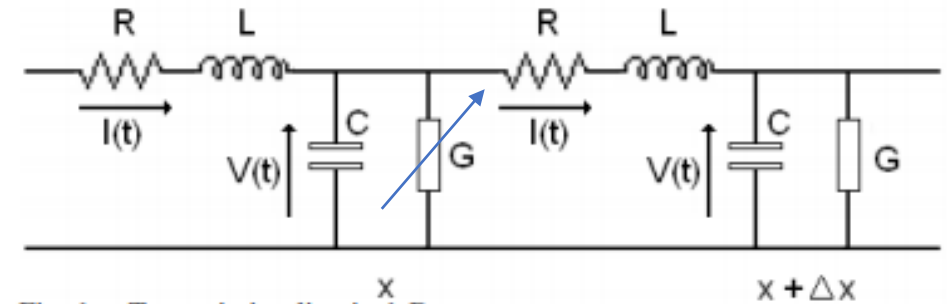


Fig. 1. Transmission line in 1-D.

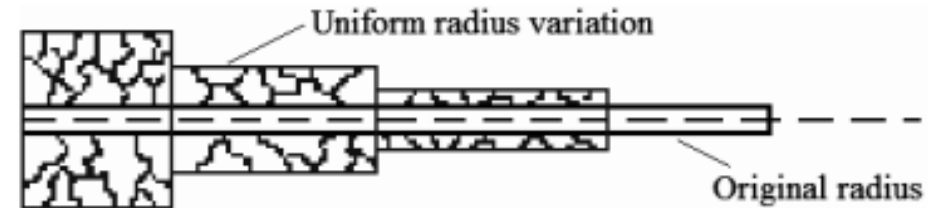
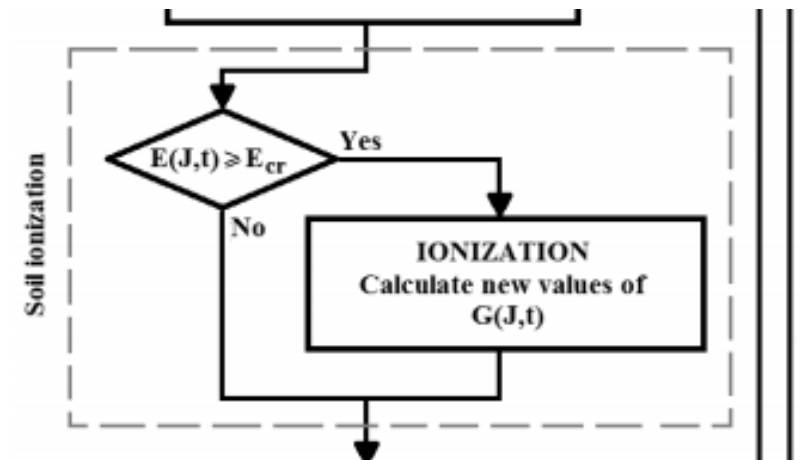


Fig. 2. Profile of the incremental electrode radius in the ionized region.



GPR considerando a ionização do solo

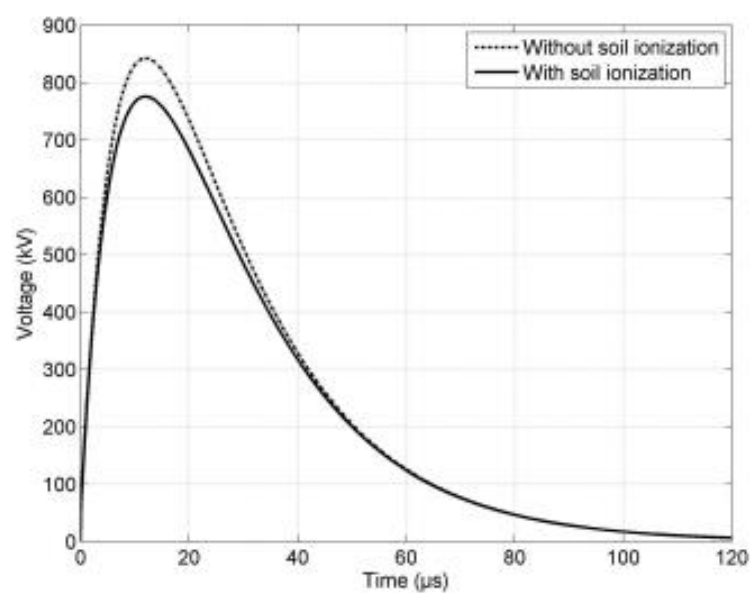


Fig. 4. Voltage at the origin of the electrode buried in soil with medium hills with forestation ( $\rho_s = 270 \Omega\text{m}$ ,  $\epsilon_r = 12$ ).

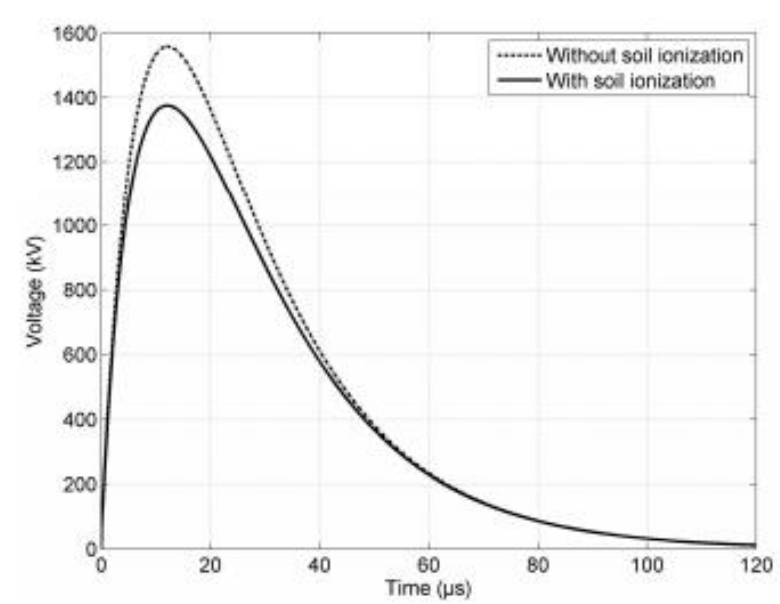


Fig. 5. Voltage at the origin of the electrode buried in rocky soil ( $\rho_s = 500 \Omega\text{m}$ ,  $\epsilon_r = 10$ ).

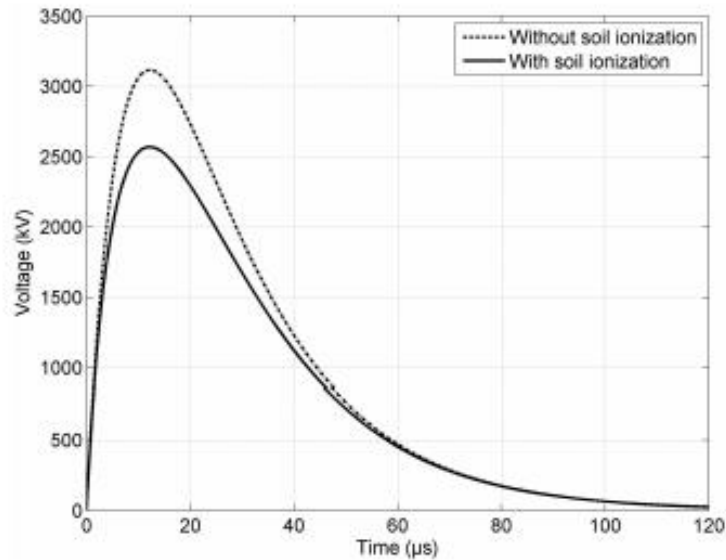


Fig. 6. Voltage at the origin of the electrode buried in urban areas ( $\rho_s = 1000 \Omega\text{m}$ ,  $\epsilon_r = 6$ ).

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# Comparação de Modelos (TLM, RLC e EMC)

- TLM-Transmission line Model
- EMC-Eletromagnetic Compatibility
- RLC-Concentrado a altas frequências;

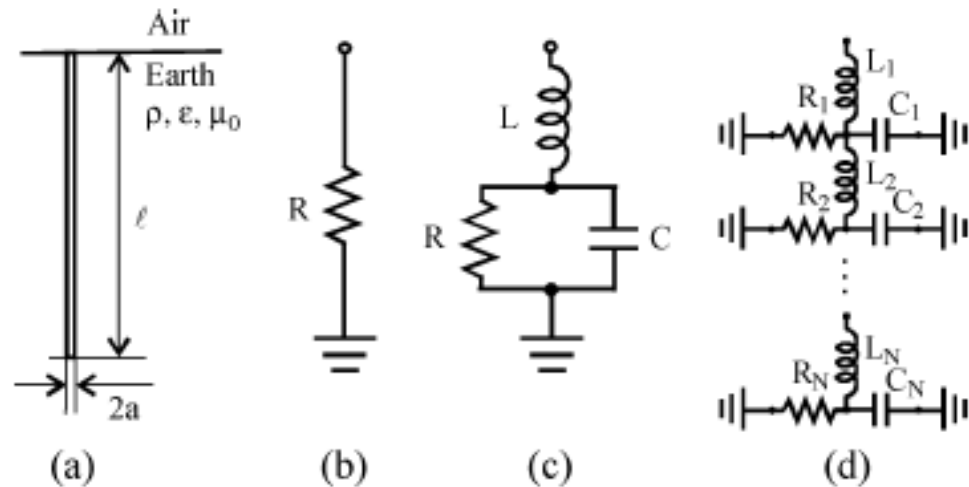


Fig. 1. Low-current models of a vertical ground rod. (a) Physical situation. (b) Low-frequency equivalent circuit. (c) High-frequency lumped R-L-C circuit. (d) High-frequency distributed parameters circuit.

## On High-Frequency Circuit Equivalents of a Vertical Ground Rod

Leonid Grcev, *Senior Member, IEEE*, and Marjan Popov, *Senior Member, IEEE*

$$R = \frac{\rho}{2\pi\ell} \left[ \log \frac{4\ell}{a} - 1 \right] (\Omega) \quad (2a)$$

$$C = 2\pi\epsilon\ell \left[ \log \frac{4\ell}{a} - 1 \right] (F)$$

$$L = \frac{\mu_0\ell}{2\pi} \left[ \log \frac{2\ell}{a} - 1 \right] (H). \quad (2b)$$

Here, symbols are given in Fig. 1(a), and  $\ell \gg a$ . Although the results from (1) are somewhat larger than those from (2), both sets of formulas lead to similar results for the impedance to ground. In this paper, we use (2) since it leads to a better match with the EM model.

Parameters of the R-L-C circuit, (1) and (2), are also used in a distributed-parameter circuit [6], [7]

$$R' = \frac{1}{G'} = R\ell (\Omega m); \quad C' = \frac{C}{\ell} (F/m); \quad L' = \frac{L}{\ell} (H/m). \quad (3)$$

The transmission line may be considered as open at the lower end, and the input impedance (equivalent to the harmonic impedance to ground) is [7]

$$Z = Z_0 \coth \gamma \ell \quad (4a)$$

$$Z_0 = \sqrt{\frac{j\omega L'}{G' + j\omega C'}}$$

$$\gamma = \sqrt{j\omega L'(G' + j\omega C')}. \quad (4b)$$

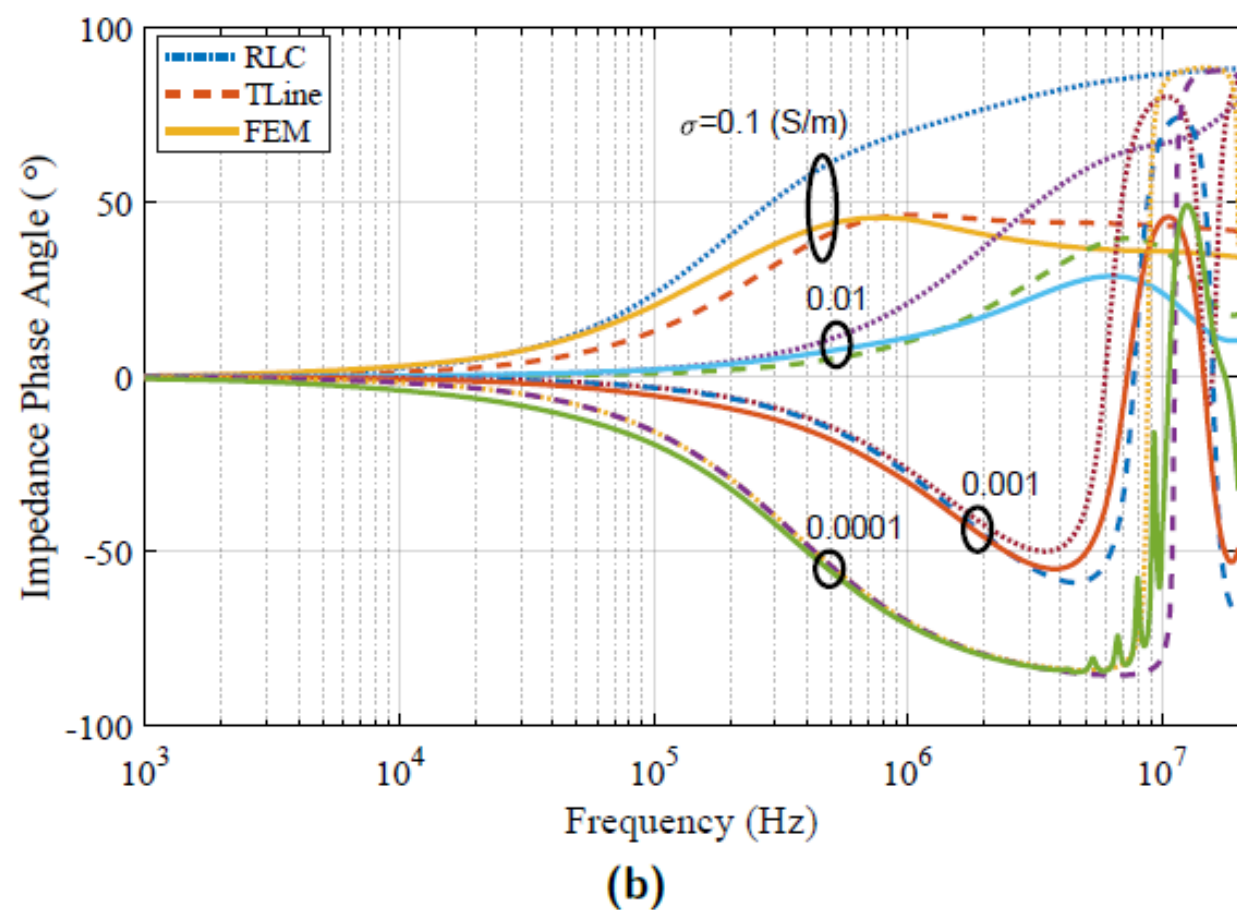
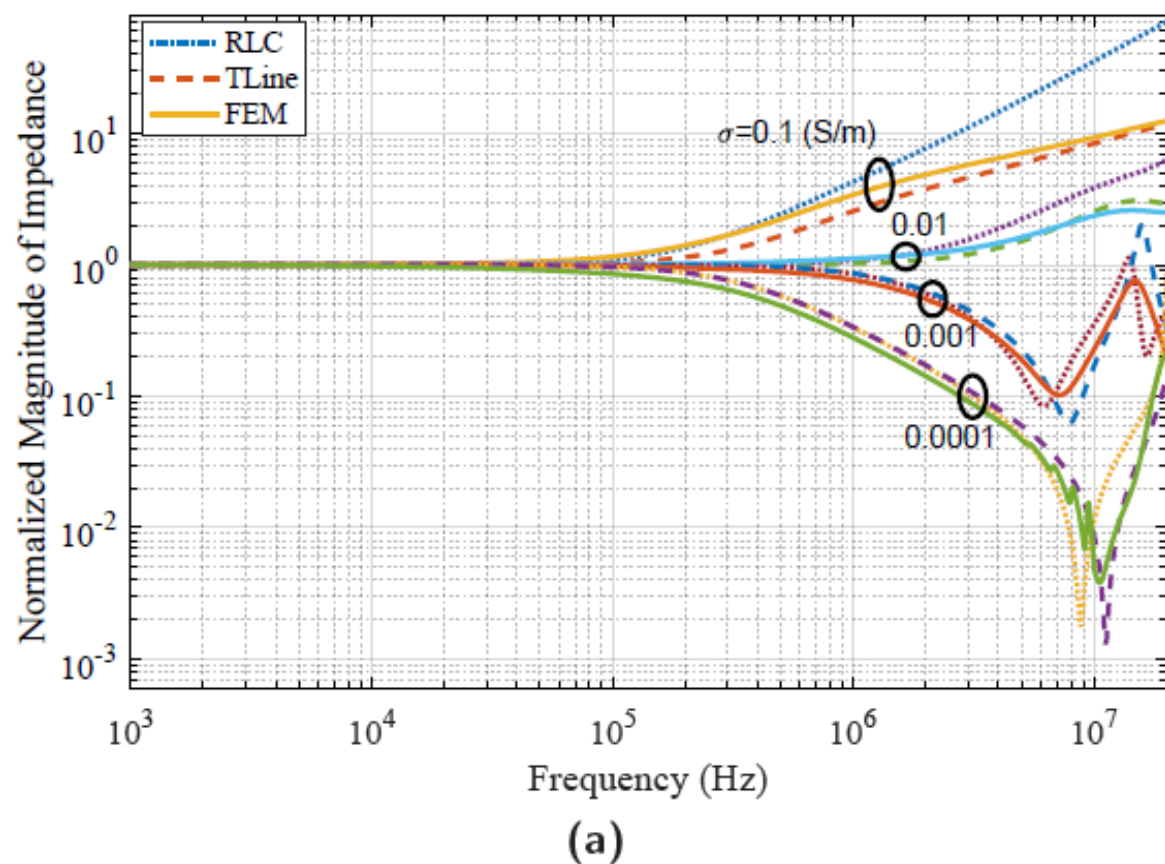
## Electromagnetic Transient Modelling of Power Transmission Line Tower and Tower-Footing Grounding System

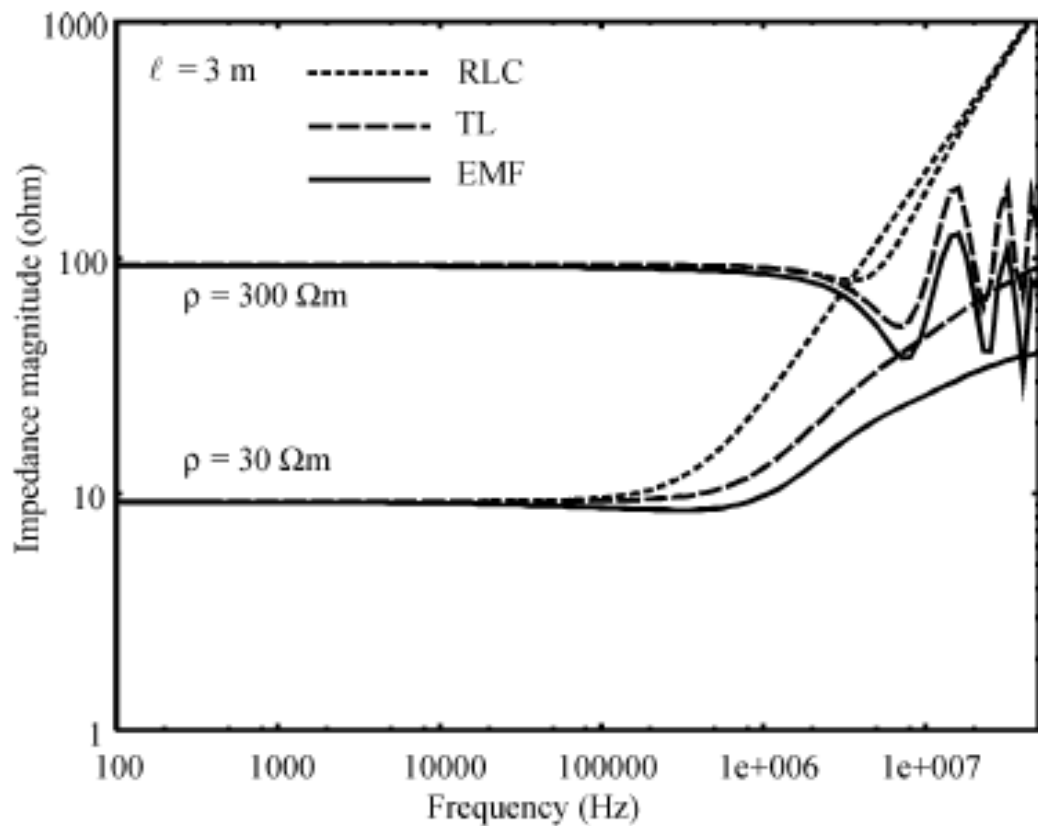
Thesis

Full-text available

January 2020

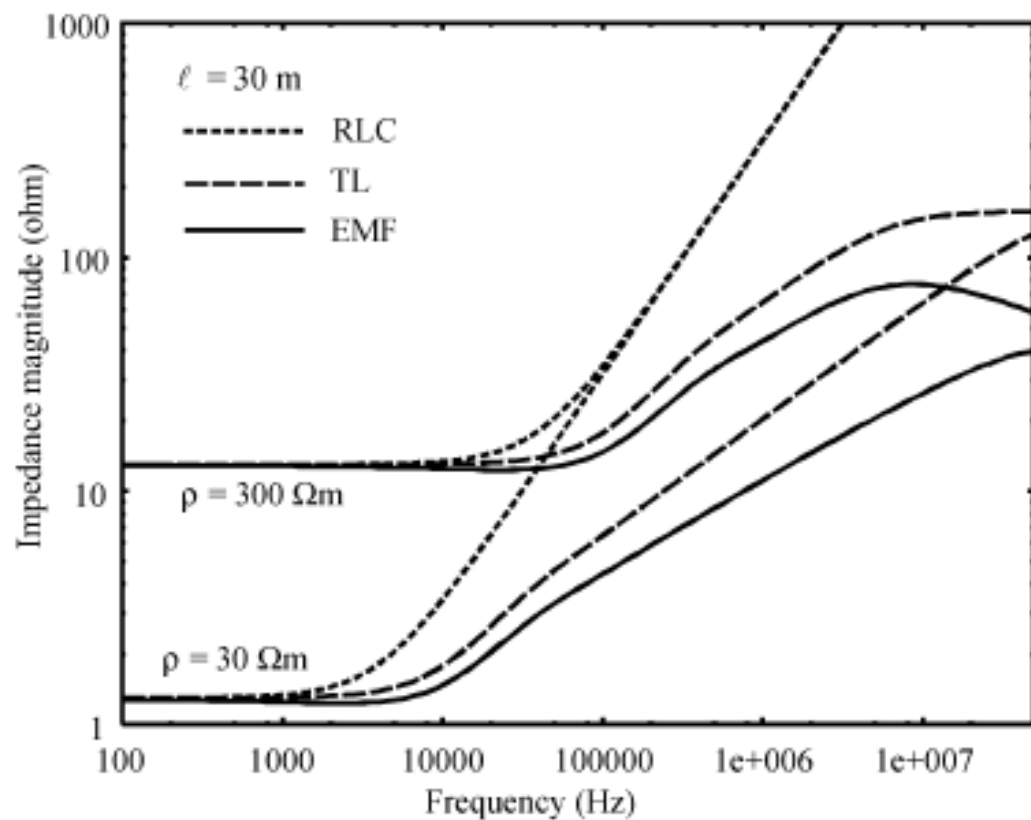
**Fig. 3.13:** Normalized magnitude (a) and phase angle (b) of harmonic impedance of 3 m vertical grounding electrode for  $\epsilon_r = 10$  along with its phase angle.





(a)

- The lumped R-L-C circuit can be used in its validity domain or for the preliminary analysis, with the knowledge that it might greatly overestimate the ground rod impedance at high frequencies.
- The discrete approximate distributed-parameter circuit reduces the overestimation of the ground rod impedance at high frequencies in comparison with the lumped R-L-C circuit. One should also check the sensitivity of the overall results to this change.



(b)

Fig. 3. Harmonic impedance to ground of (a) short  $\ell = 3$  m and (b) long  $\ell = 30$ -m ground rods in more conductive ( $\rho = 30 \Omega\text{m}$ ) and in less conductive ( $\rho = 300 \Omega\text{m}$ ) soil.

- If further reduction of the overestimation of the impedance to ground at high frequencies is needed, the EM model might be used. Equivalent circuit parameters can be determined by the described curve matching procedure.

# 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);
  - ❖ Métodos numéricos empregados na resolução das equações de Maxwell (Aula-2);
  - ❖ Modelos a parâmetros concentrados (Aula-3);

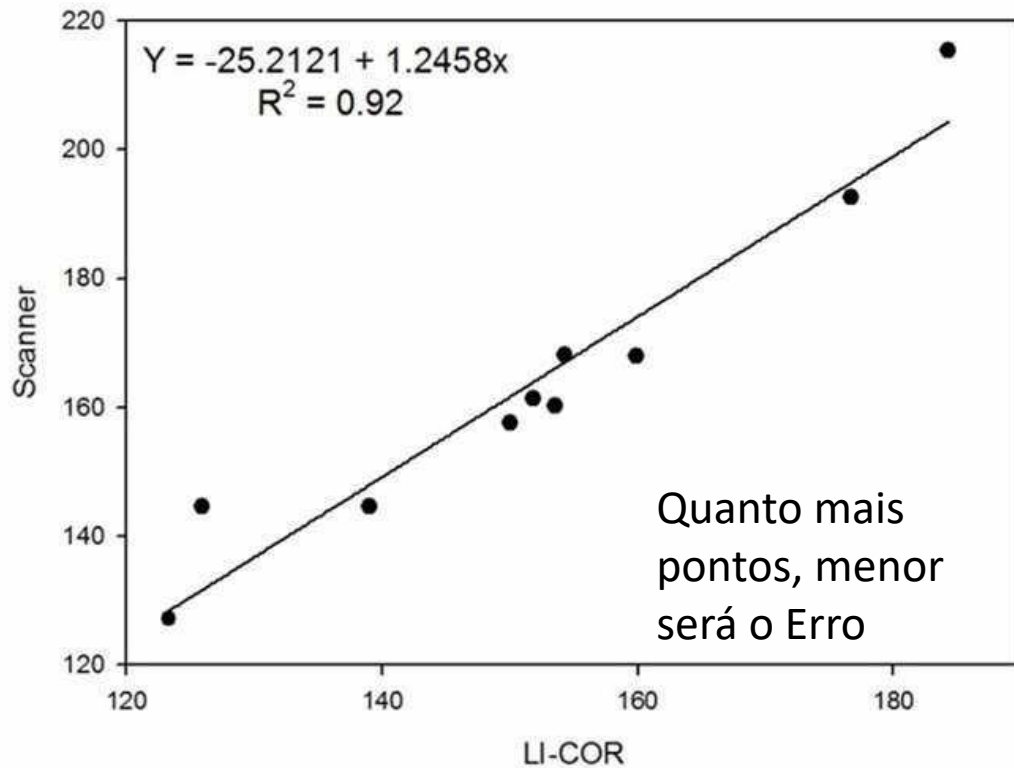
# Modelo a par. Concentrados-Vector Fitting

- Vector fitting é uma técnica na qual um circuito elétrico concentrado é ajustado ('fitted') para uma dada resposta em função da frequência  $Y(s)$ ;
- Diversos circuitos podem ser ajustados a partir de uma curva;
- O erro entre a função original e a função ajustada depende do número de polos escolhidos;
- Esse método se baseia no método dos mínimos quadrados;
- Uma vez obtido o circuito equivalente, esse pode ser inserido em qualquer software EMTP.

# Vector Fitting conceitos



Mét. Dos Mínimos Quadrados



$$\begin{cases} \dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}u(t) \\ \mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) + \mathbf{D}u(t) \end{cases}$$

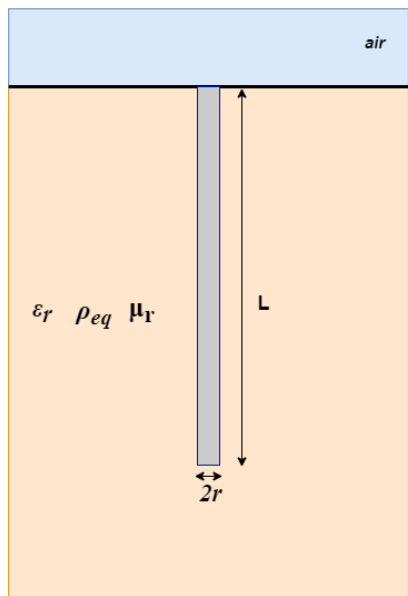
$$\mathcal{L}\{\dot{\mathbf{x}}(t)\} = \mathcal{L}\{\mathbf{A}\mathbf{x}(t) + \mathbf{B}u(t)\} \quad \mathcal{L}\{\mathbf{y}(t)\} = \mathcal{L}\{\mathbf{C}\mathbf{x}(t) + \mathbf{D}u(t)\}$$

$$\mathbf{G}(s) = \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B} + \mathbf{D}$$

$$G_{ij}(s) = \frac{\det \begin{bmatrix} s\mathbf{I} - \mathbf{A} & -\mathbf{B}_j \\ \mathbf{C}_i & \mathbf{D}_{ij} \end{bmatrix}}{\det[s\mathbf{I} - \mathbf{A}]} \approx Y_{fit}(s)$$

# Etapas do VF

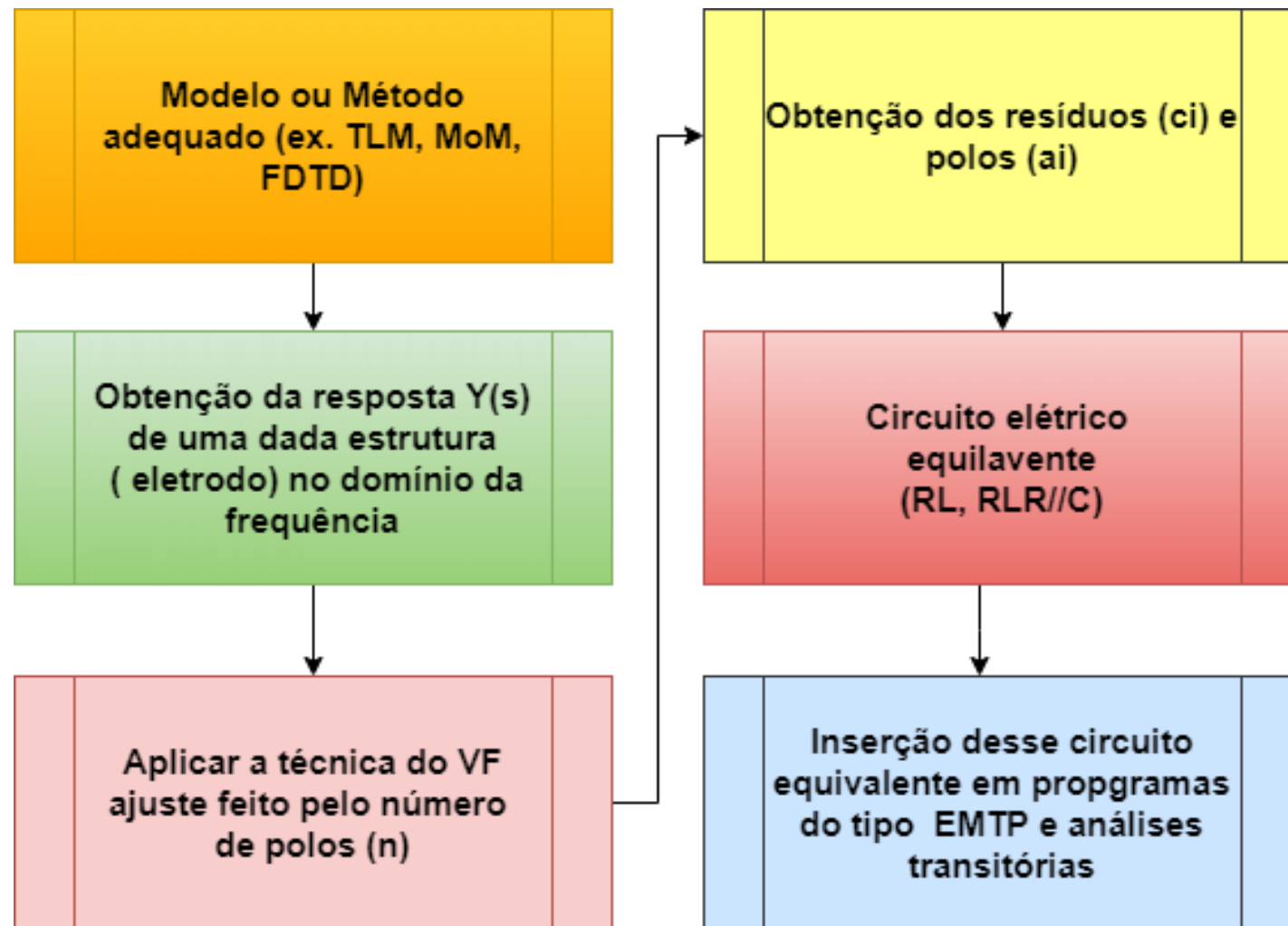
$Y(s)$  ou  $Z(s)$



$$Y(s) = \frac{I(s)}{V(s)}$$

$$Y_A(s) = D + sE + \sum_{i=1}^n \frac{c_i}{s - a_i}$$

Onde  $c_i$  é o residuo e  $a_i$  é o polo de cada ramo.  
 $n$  é o número de polos

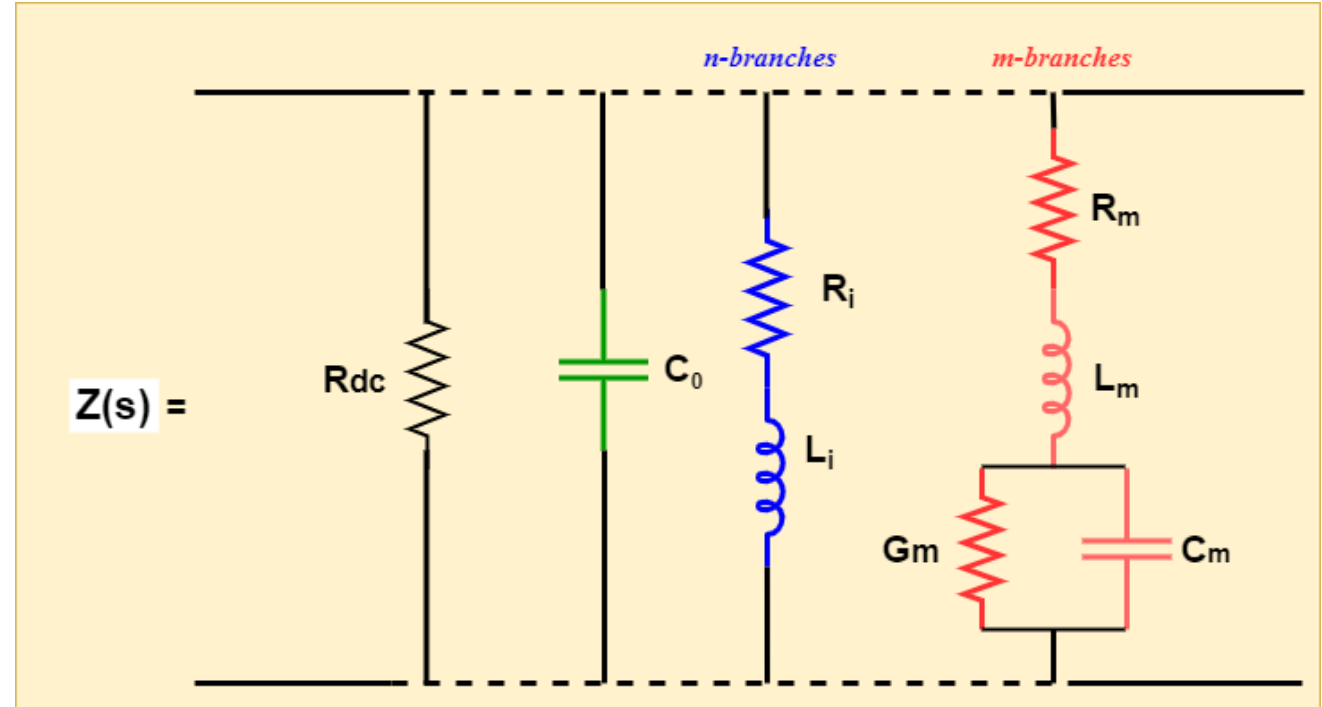


O VR fornece o circuito elétrico mais próximo (menor error) para uma dada  $Y(s)$ .

# Admitância de aterramento

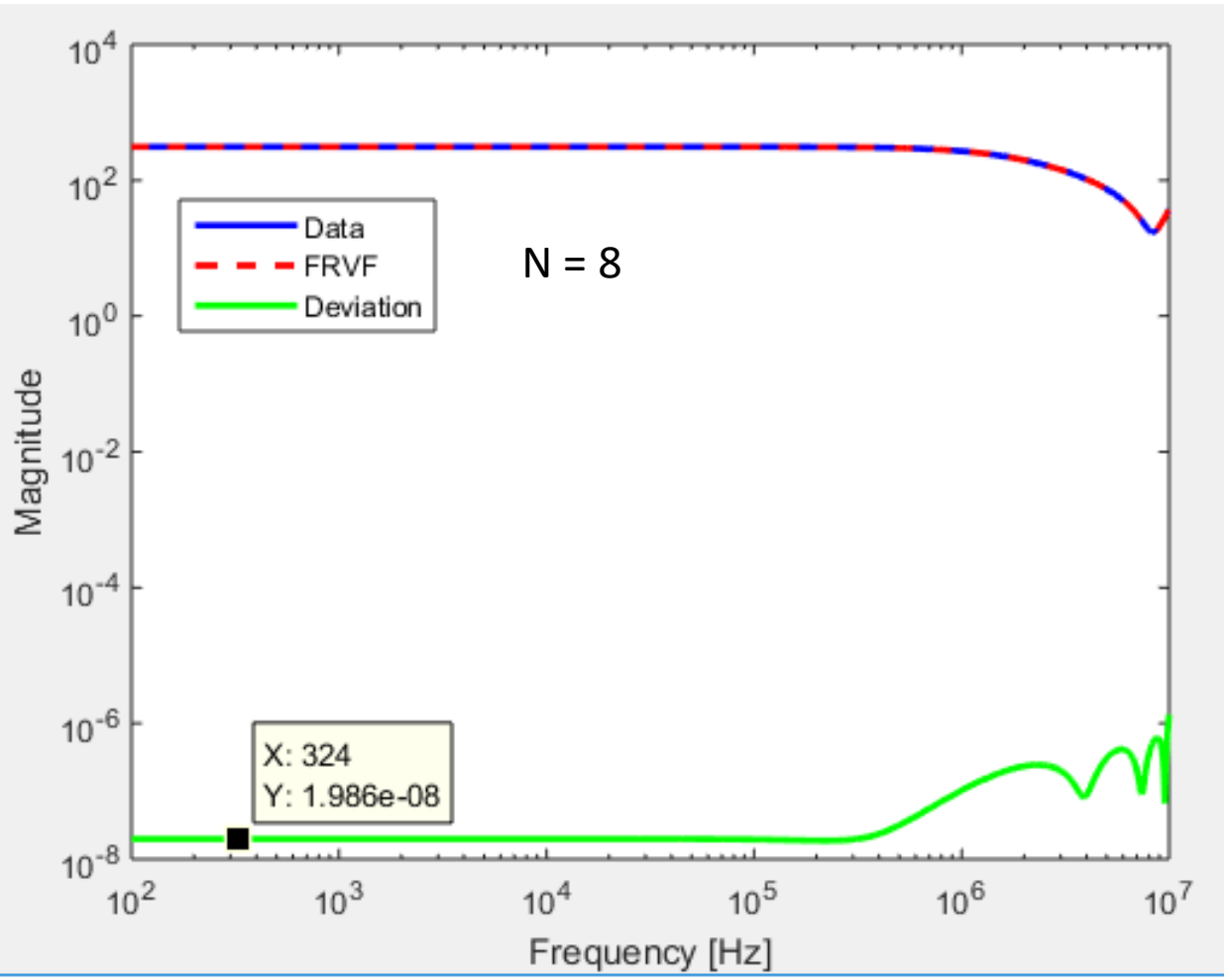
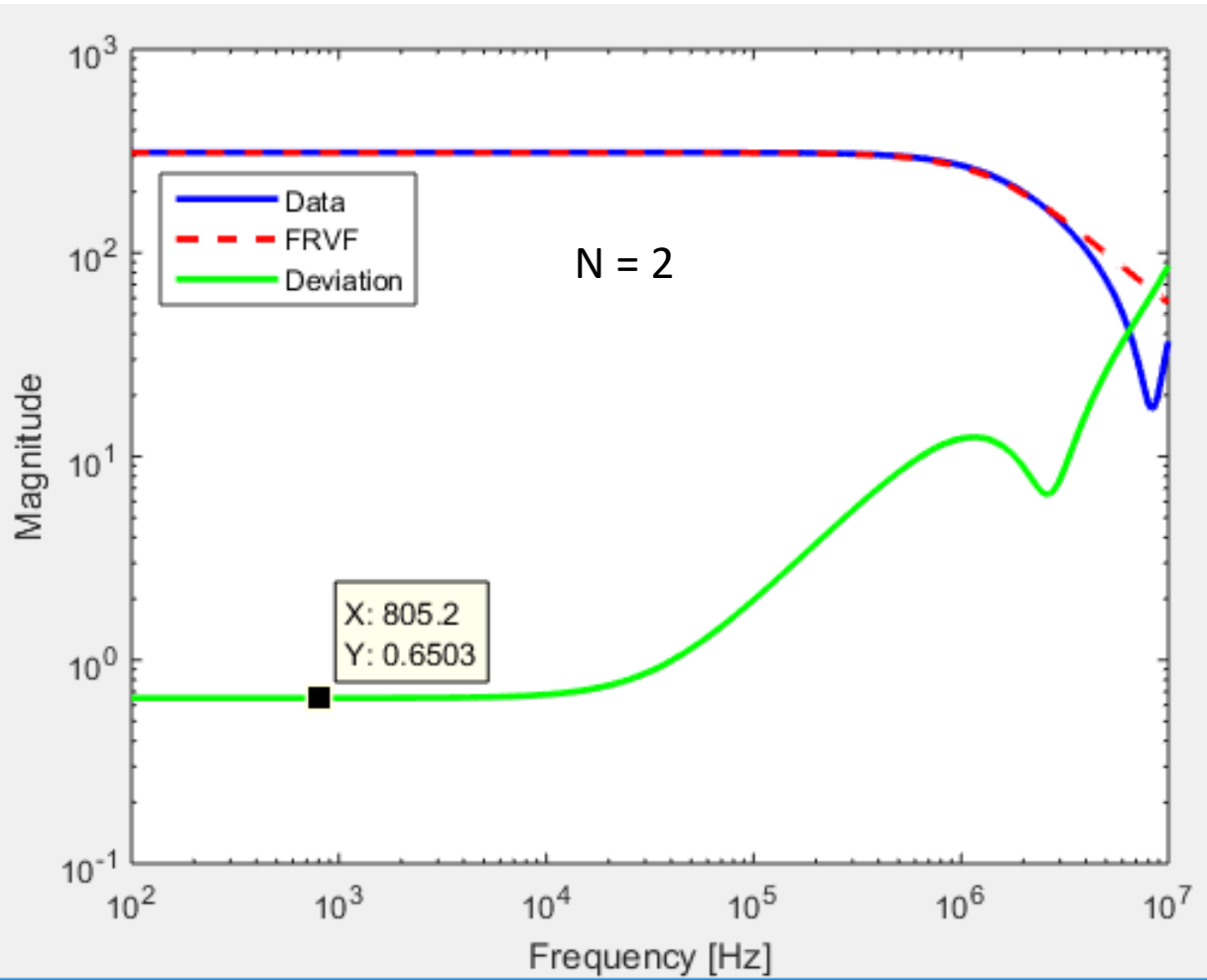
$$Y_A(s) = D + sE + \sum_{i=1}^N \frac{c_i}{s - a_i}$$

Onde  $c_i$  é o residuo e  $a_i$  é o polo de cada ramo.  
O circuito RL sintetiza polos reais;  
O circuito RLGC sintetiza polos complexos;  
A representação por circuito não é única, pois depende do número de polos (N).

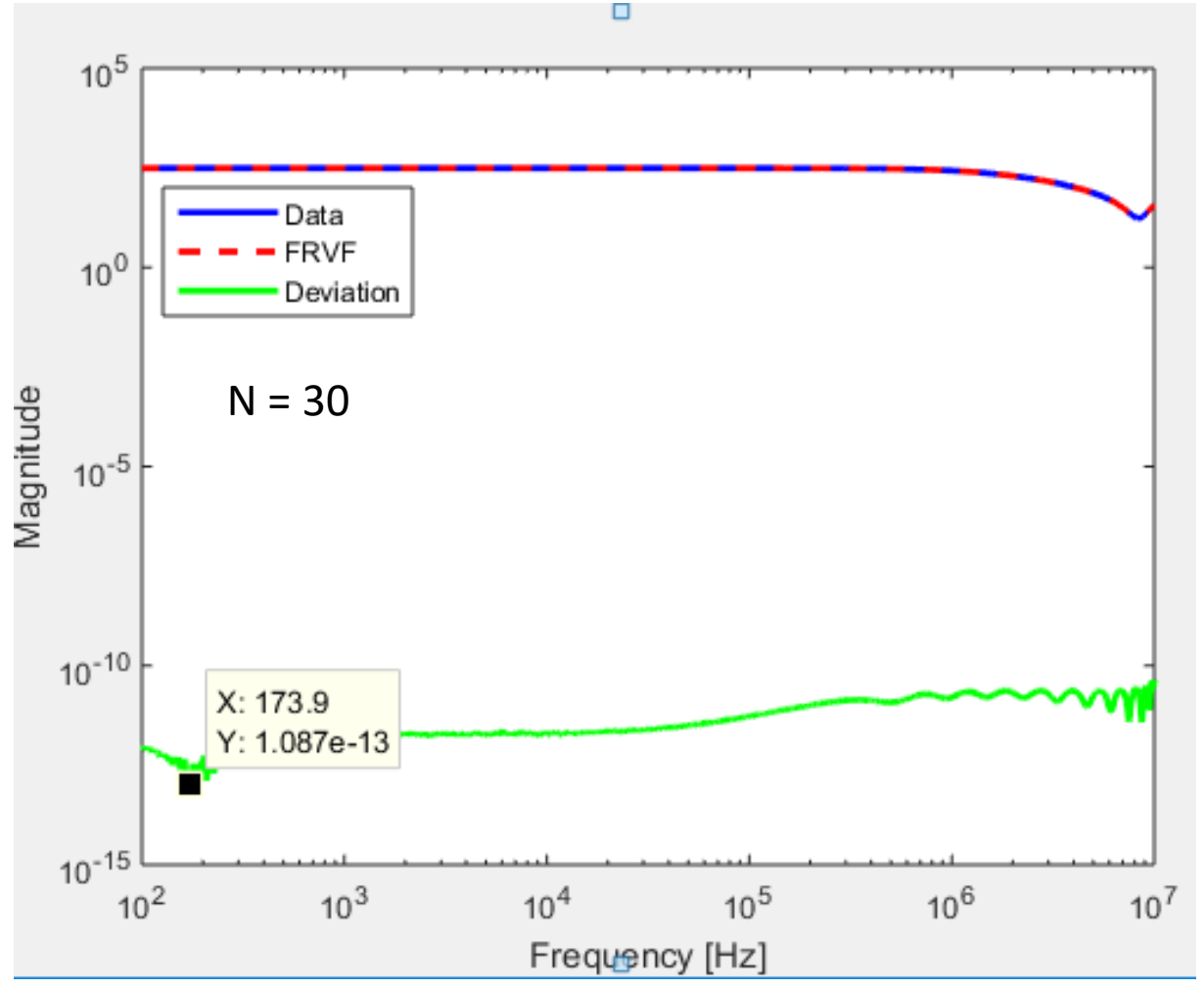
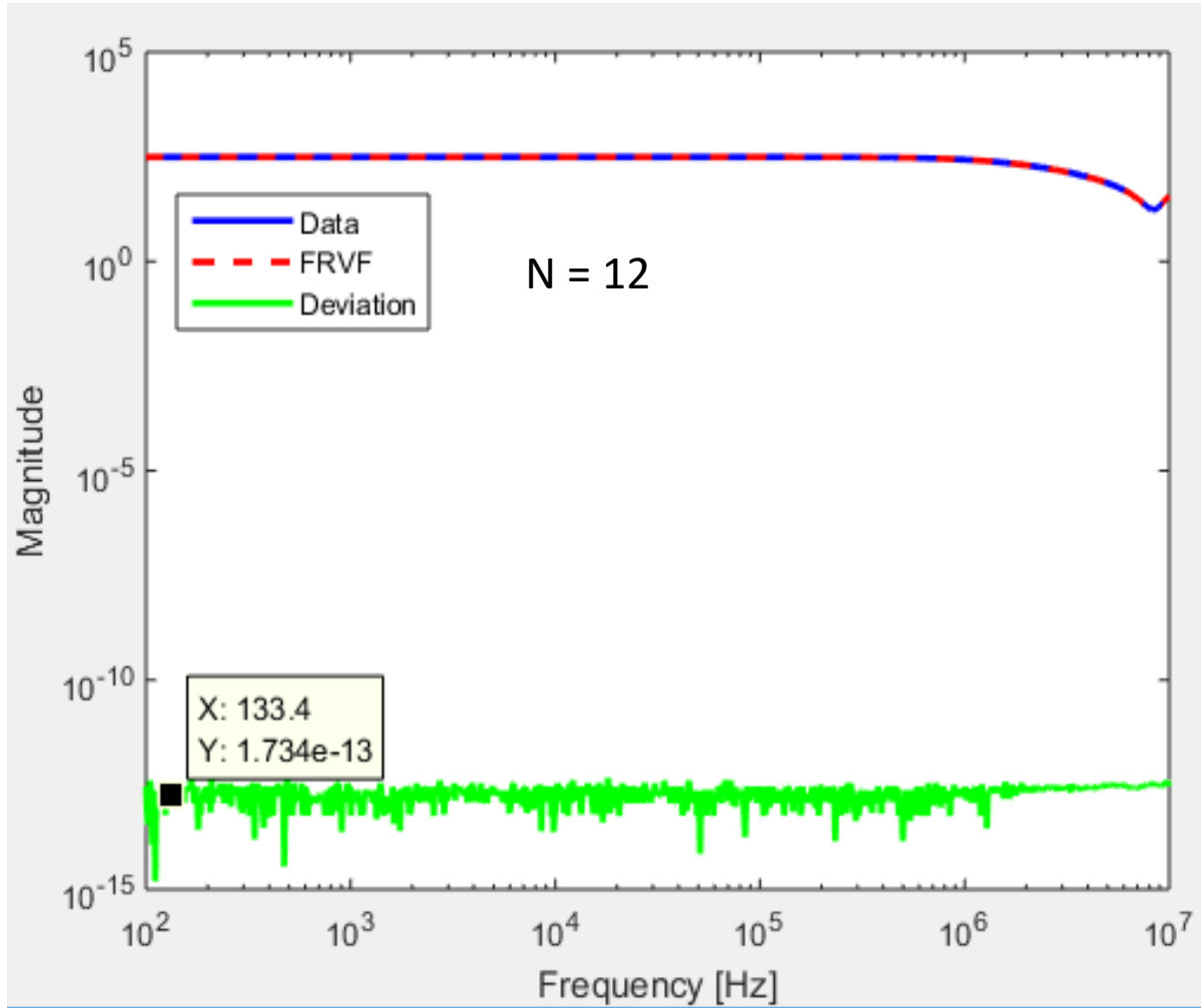




# Influência do número de polos (N)



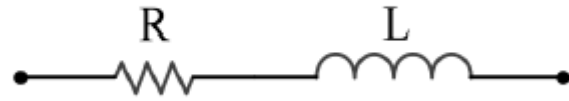
# Influência do número de polos (n)



# Cálculo dos parâmetros de circuitos

## Polos Reais

$$F_R(s) = \frac{c_i}{s - a_i}$$



$$Y_R(s) = \frac{\left(\frac{1}{L}\right)}{s + \left(\frac{R}{L}\right)}$$

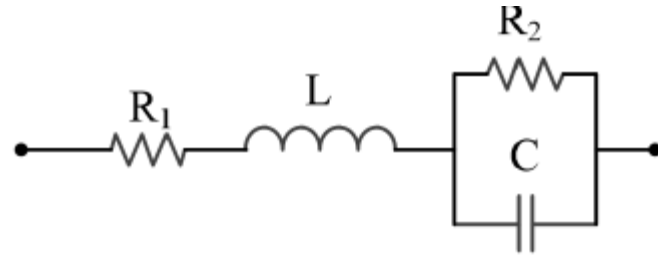
$$L = \frac{1}{c_i}$$

$$R = -\frac{a_i}{c_i}$$

## Polos Complexos Conjugados

$$F_C(s) = \frac{c_1}{s - a_1} + \frac{c_2}{s - a_2}$$

$$F_C(s) = \frac{(c_1 + c_2)s - (c_1a_2 + c_2a_1)}{s^2 - (a_1 + a_2)s + (a_1a_2)}$$



$$Y_c = \frac{1}{L} \frac{s + \left(\frac{1}{R_2C}\right)}{s^2 + \left(\frac{R_1}{L} + \frac{1}{R_2C}\right)s + \left(\frac{R_1}{LR_2C} + \frac{1}{LC}\right)}$$

$$L = \frac{1}{(c_1 + c_2)}$$

$$R_1 = \frac{K}{(c_1 + c_2)}$$

$$k = \left[ -(a_1 + a_2) + \left( \frac{c_1a_2 + c_2a_1}{c_1 + c_2} \right) \right]$$

$$C = \frac{(c_1 + c_2)}{a_1a_2 + kQ}$$

$$R_2 = -\frac{1}{CQ}$$

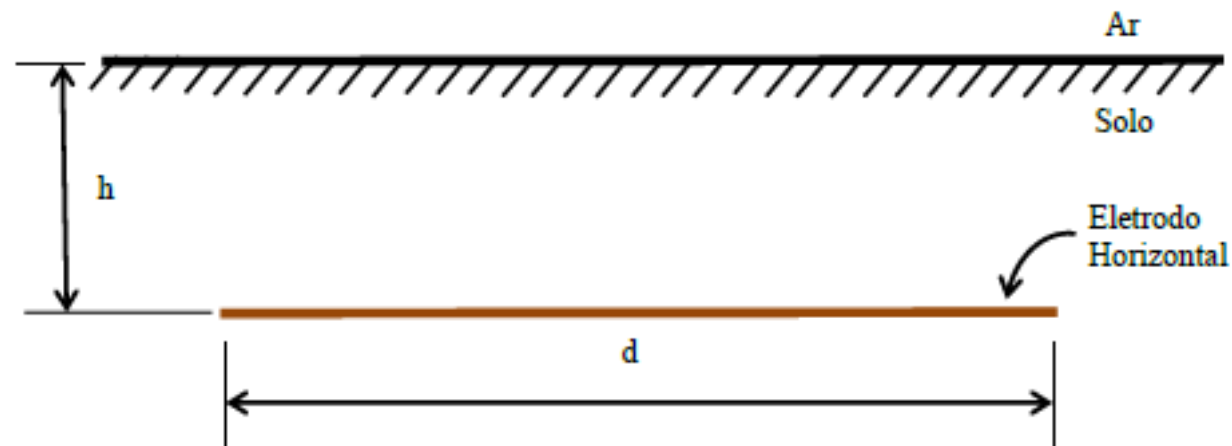
$$Q = \frac{c_1a_2 + c_2a_1}{c_1 + c_2}$$

# Exemplo

## Eletrodo horizontal

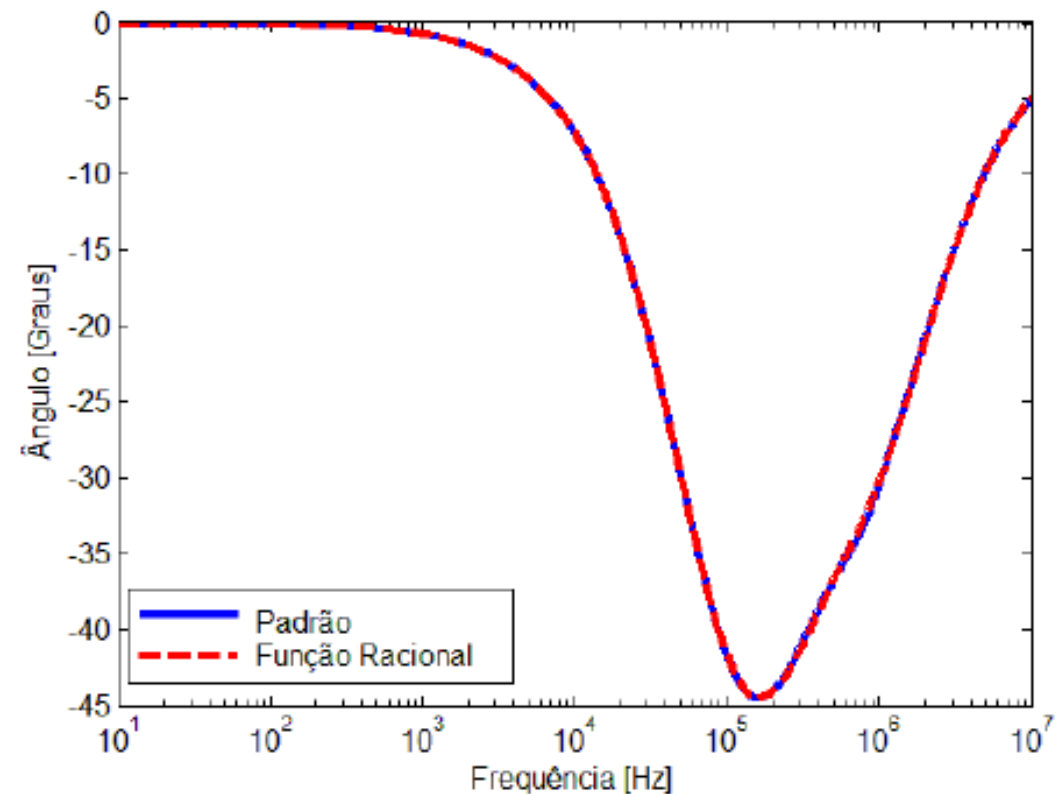
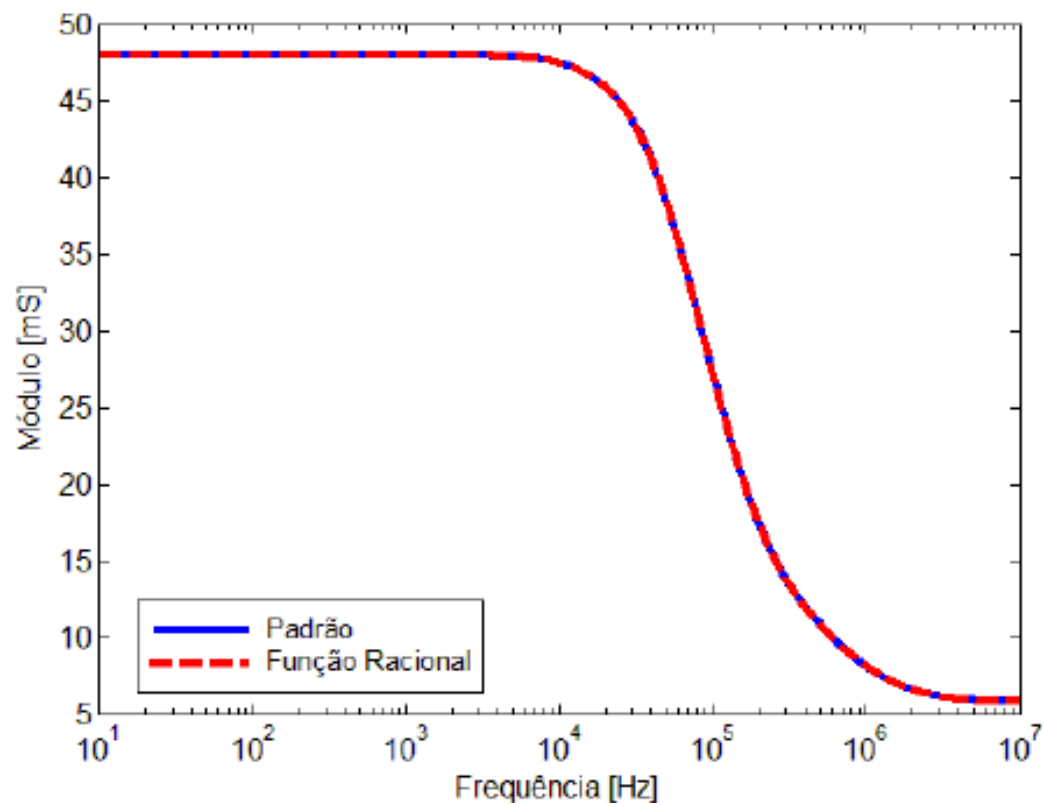
Raio = 7mm , L = 100 m,  $\rho = 1000 \Omega\text{m}$

$$Y_A(s) = \frac{1}{Z_c} \text{tgh}(yd)$$



(a)

(b)

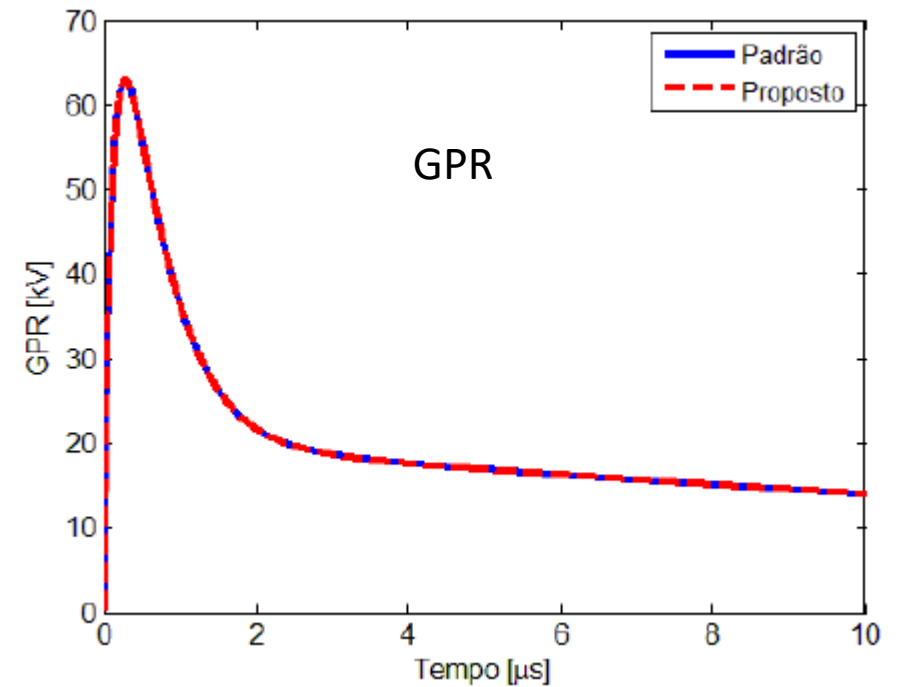
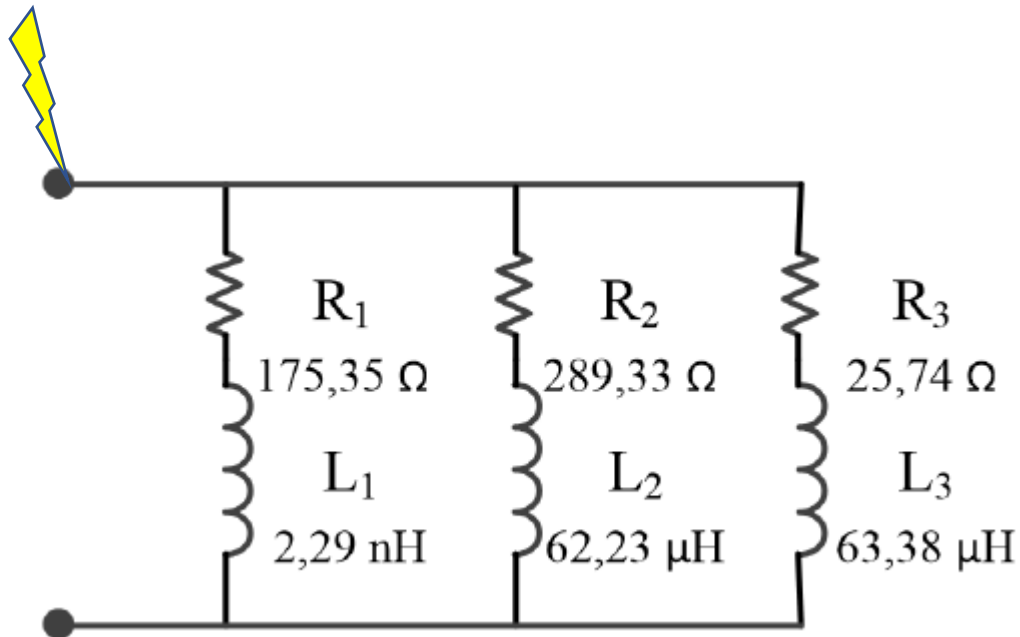


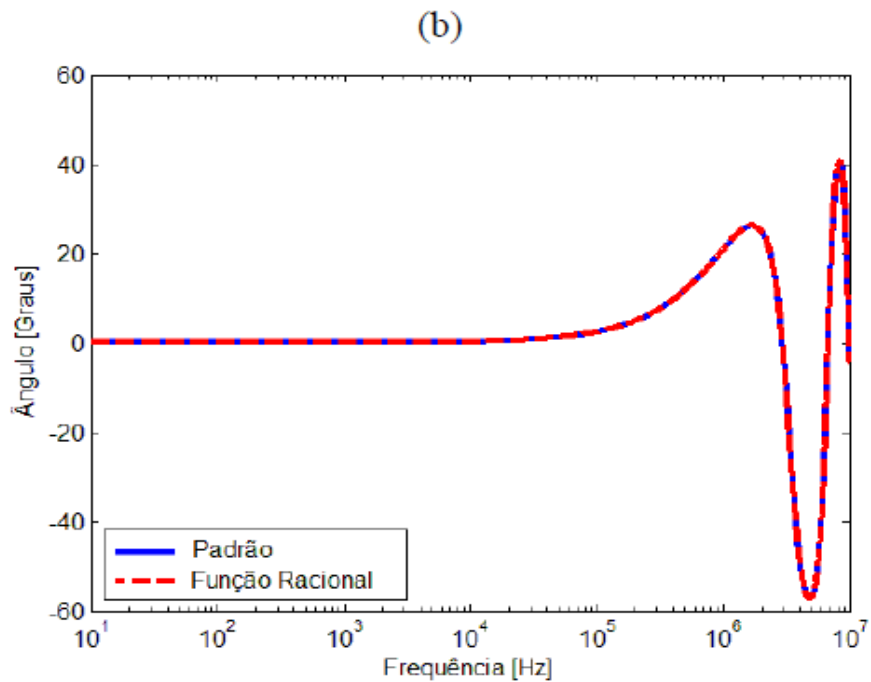
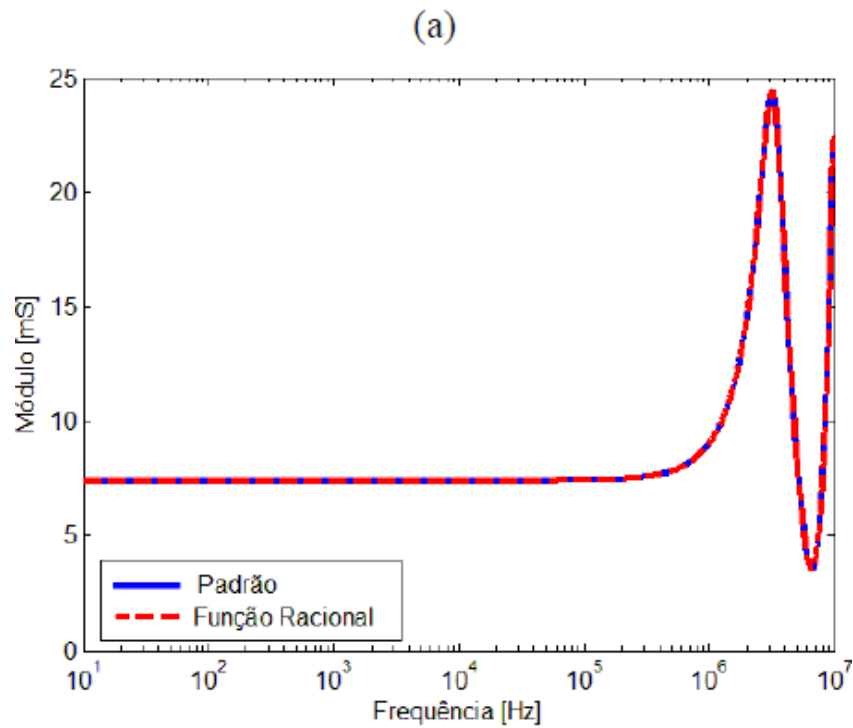
# Eletrodo Horizontal

3 ramos RL -polos reais

$$F_R(s) = \frac{c_i}{s - a_i} \quad L = \frac{1}{c_i} \quad R = -\frac{a_i}{c_i}$$

$$F(s) = \frac{4,3626 \times 10^8}{s - (-7,6497 \times 10^{10})} + \frac{1,6071 \times 10^4}{s - (-4,6497 \times 10^6)} + \frac{1,5779 \times 10^4}{s - (-4,0617 \times 10^5)}$$





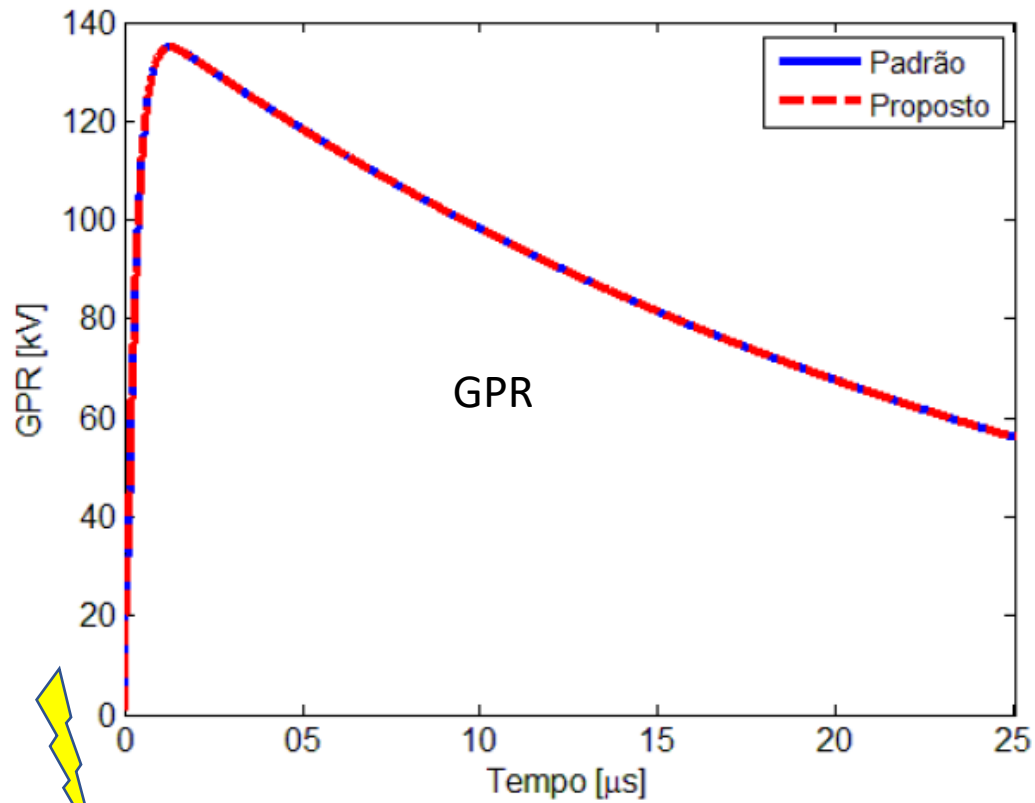
# Eletrodo horizontal

Raio = 7mm , L = 10 m,  $\rho = 1000 \Omega\text{m}$

Polo real

Polos complexos

$$FR(s) = \frac{1,2133 \times 10^4}{s - (-1,3894 \times 10^8)} + \frac{(1,1788 \times 10^5 - j3,2809 \times 10^4)}{s - (-5,6470 \times 10^6 + j2,0289 \times 10^7)} + \frac{(1,1788 \times 10^5 + j3,2809 \times 10^4)}{s - (-5,6470 \times 10^6 - j2,0289 \times 10^7)} + \frac{(1,1787 \times 10^5 - j1,0563 \times 10^4)}{s - (-5,6470 \times 10^6 + j6,2927 \times 10^7)} + \frac{(1,1787 \times 10^5 + j1,0563 \times 10^4)}{s - (-5,6470 \times 10^6 - j6,2927 \times 10^7)} + \frac{(1,4090 \times 10^5 - j2,7333 \times 10^3)}{s - (-6,2200 \times 10^6 + j1,0675 \times 10^8)} + \frac{(1,4090 \times 10^5 + j2,7333 \times 10^3)}{s - (-6,2200 \times 10^6 - j1,0675 \times 10^8)} + \frac{(1,3293 \times 10^6 + j9,1372 \times 10^3)}{s - (-1,2551 \times 10^7 + j2,5381 \times 10^8)} + \frac{(1,3293 \times 10^6 - j9,1372 \times 10^3)}{s - (-1,2551 \times 10^7 - j2,5381 \times 10^8)}$$



1 ramo RL polo real  
4 ramos RLRC polos complexos conjugados

$$F_C(s) = \frac{c_1}{s - a_1} + \frac{c_2}{s - a_2}$$

$$L = \frac{1}{(c_1 + c_2)}$$

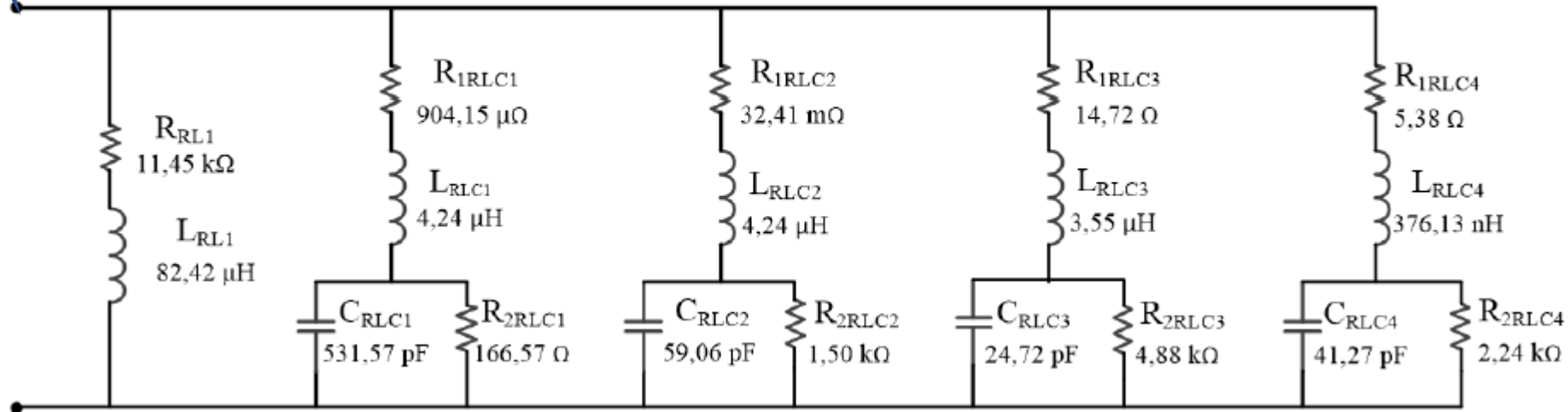
$$R_1 = \frac{K}{(c_1 + c_2)}$$

$$k = \left[ -(a_1 + a_2) + \left( \frac{c_1 a_2 + c_2 a_1}{c_1 + c_2} \right) \right]$$

$$C = \frac{(c_1 + c_2)}{a_1 a_2 + kQ}$$

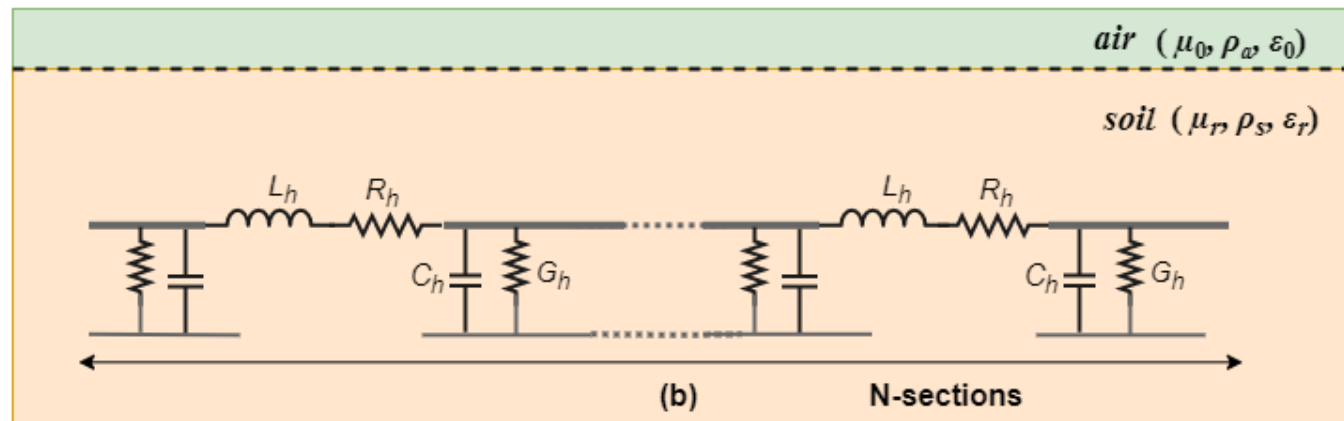
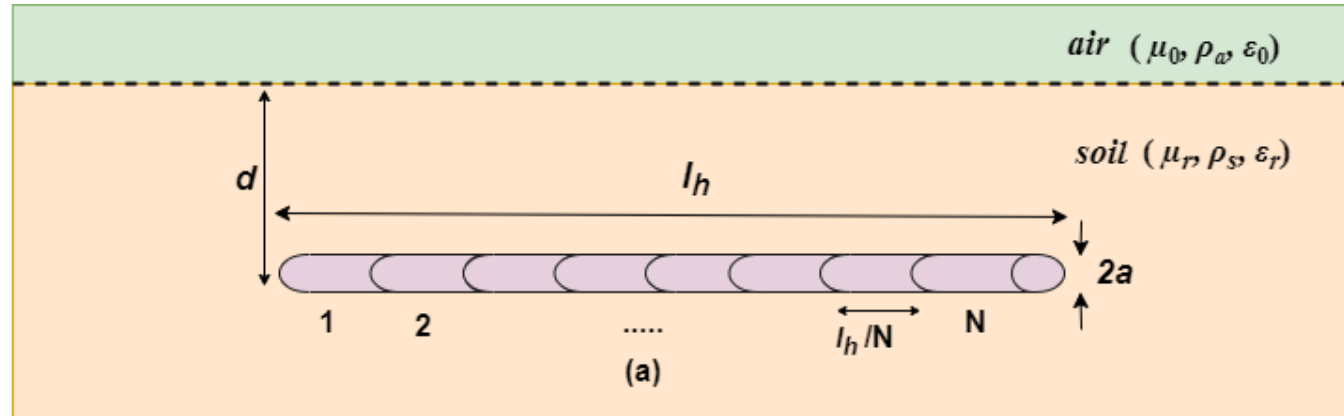
$$R_2 = -\frac{1}{CQ}$$

$$Q = \frac{c_1 a_2 + c_2 a_1}{c_1 + c_2}$$



# Modelo a Parâmetros Concentrados (circuitos em cascata)

- Nesse modelo, o eletrodo horizontal ou vertical pode ser representado por uma cascata de circuitos pi.
- O eletrodo é dividido em  $N$  segmentos de igual tamanho.
- Mas como escolher propriamente  $N$  ?



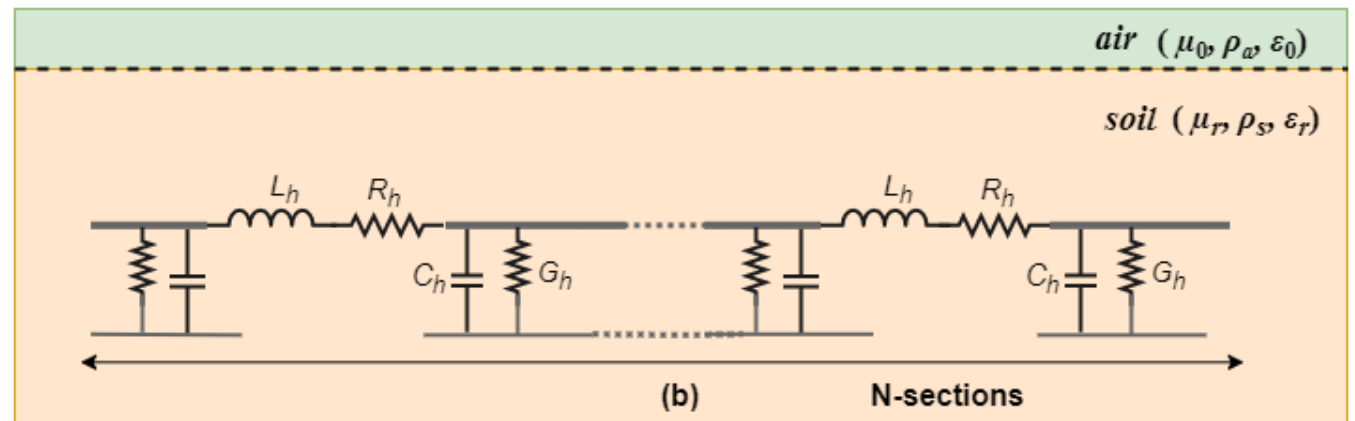
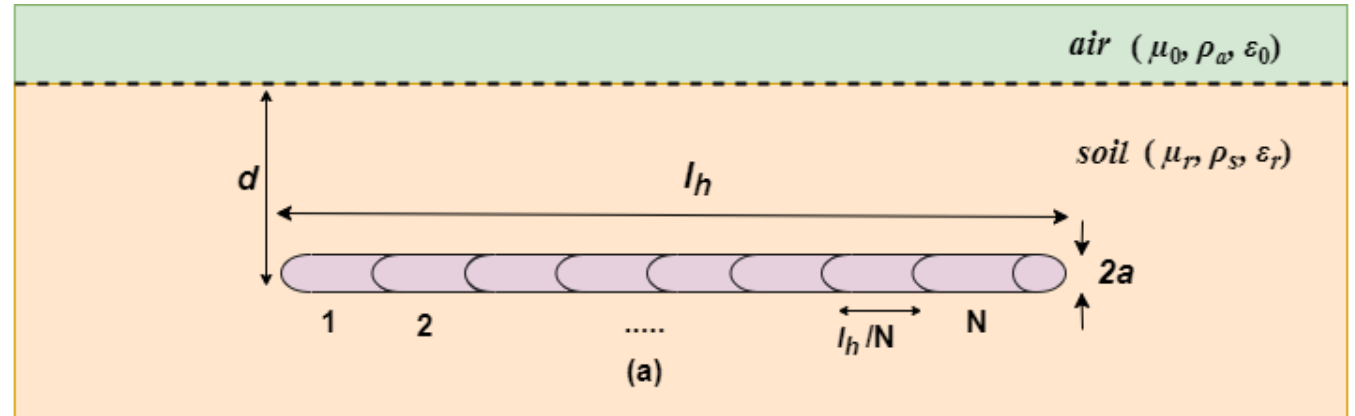


# Teoria Eletromagnética

## corrente filamentar

- Os parâmetros  $R_h$ ,  $L_h$ ,  $G_h$  e  $C_h$  são a resistência, indutância, condutância e capacitância.
- Os parâmetros elétricos são  $\mu$ ,  $\epsilon$  e  $\rho$  são a permeabilidade, permissividade e resistividade.
- O comprimento elementar é definido por:

$$l_e = l_h / N$$



# Cálculo dos parâmetros elétricos

As equações de Sunde podem ser empregadas quando  $l_e \ll d$

$$L_h = \frac{\mu_0 l_e}{2\pi} \ln \left( \frac{2l_e}{\sqrt{2ad}} - 1 \right); \quad G_h = \frac{C_h}{\rho_s \epsilon_0 \epsilon_r}$$

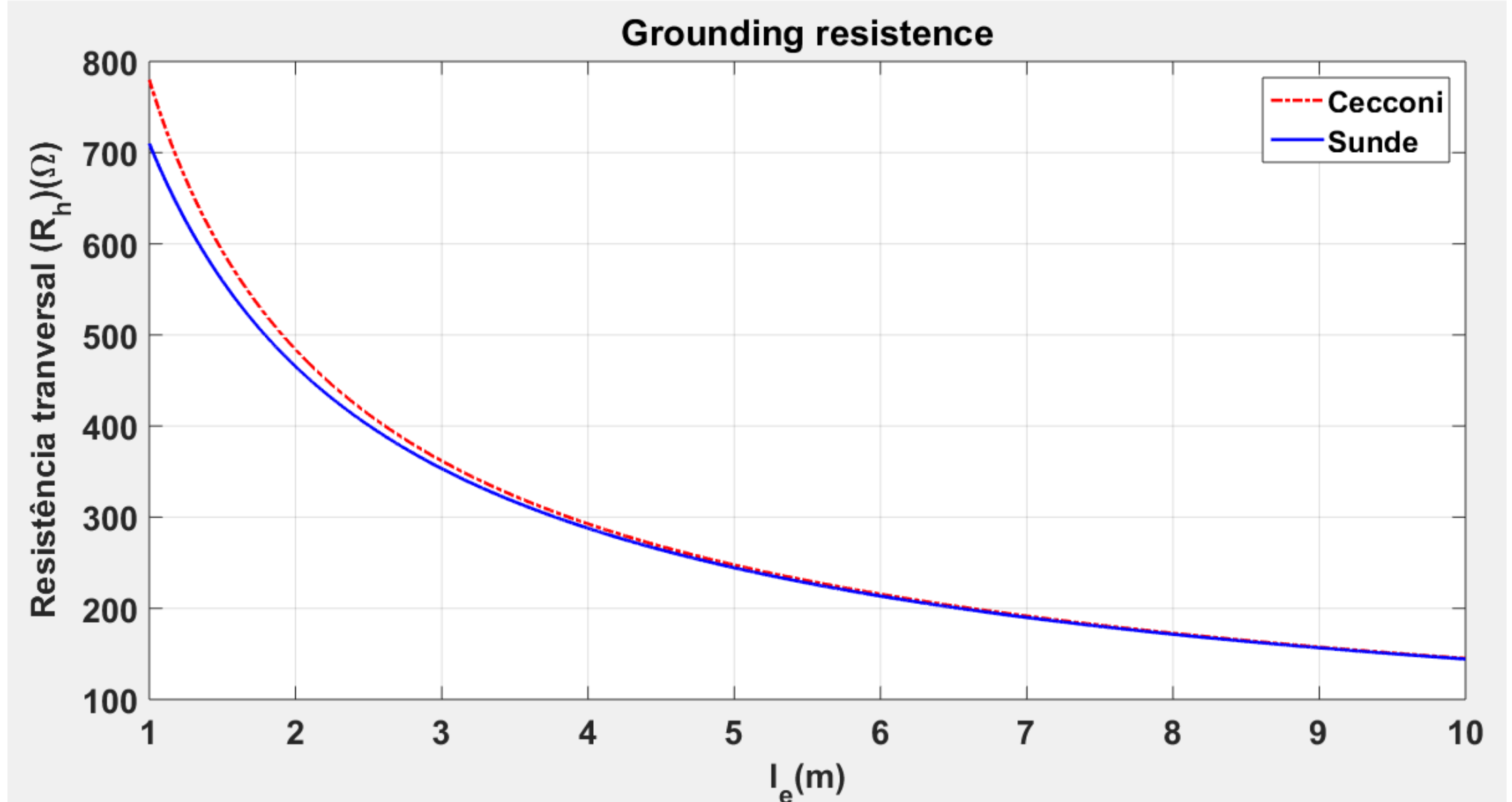
$$C_h = \frac{\pi \epsilon_0 \epsilon_r l_e}{\ln \left( \frac{2l_e}{\sqrt{2ad}} - 1 \right)}; \quad R_h = \frac{\rho_c}{\pi a^2}$$

Se  $l_e \gg d$ , as equações de Sunde não podem ser empregadas. Nesse caso, são propostas as fórmulas de Cecconi:

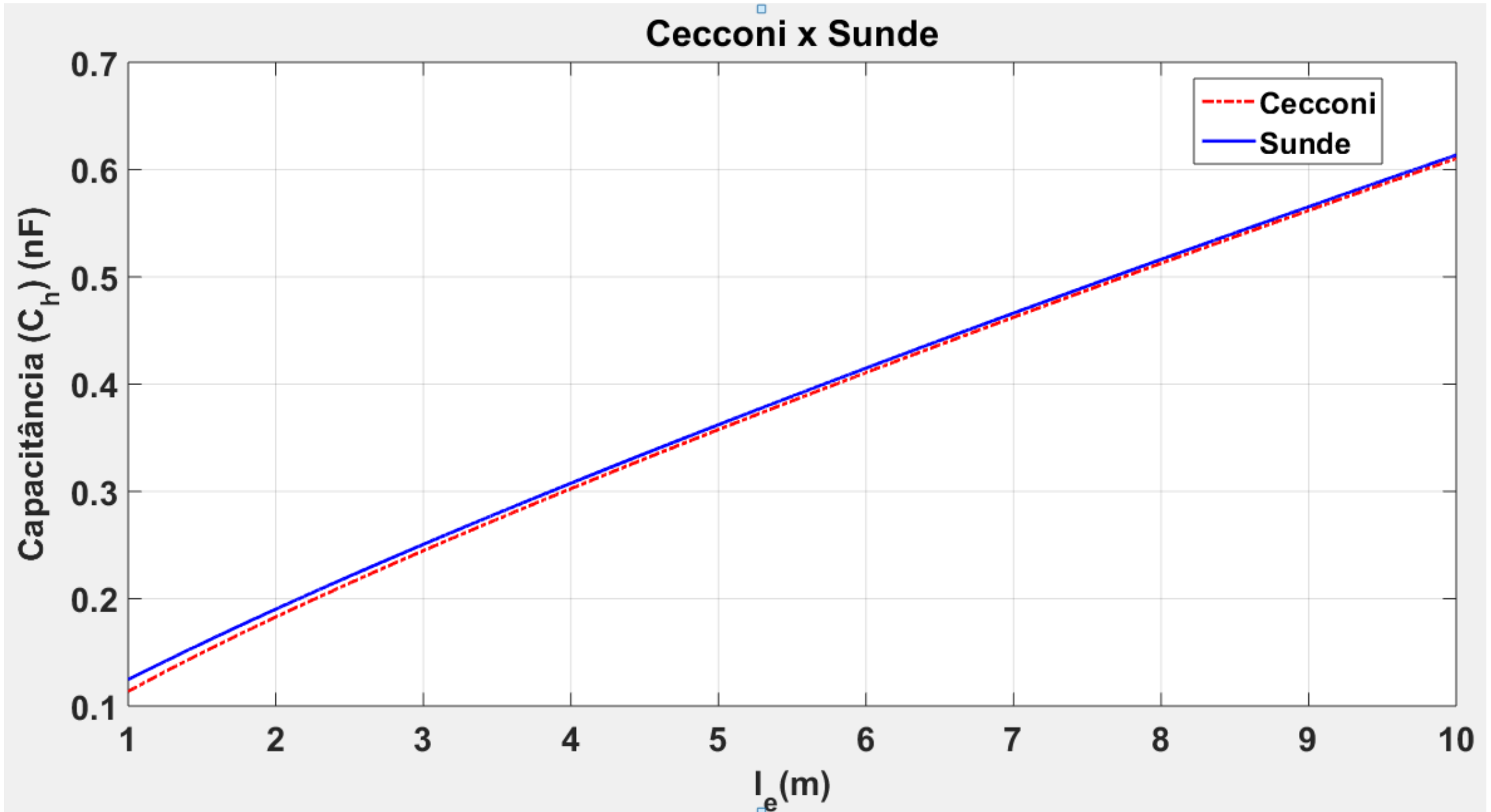
$$L_h = \frac{\mu_0 l_e}{4\pi} \left[ \ln \frac{2l_e}{r_h} + \ln \frac{l_e}{d} - 2 + \frac{2d}{l_e} - \frac{d^2}{l_e^2} + \frac{1}{2} \frac{d^4}{l_e^4} \right];$$

$$C_h = \frac{\mu_0 \epsilon_0 \epsilon_r l_e^2}{2L_h}; \quad G_h = \frac{C_h}{\rho_s \epsilon_0 \epsilon_r}; \quad R_h = \frac{\rho_c}{\pi r_h^2} \quad (5)$$

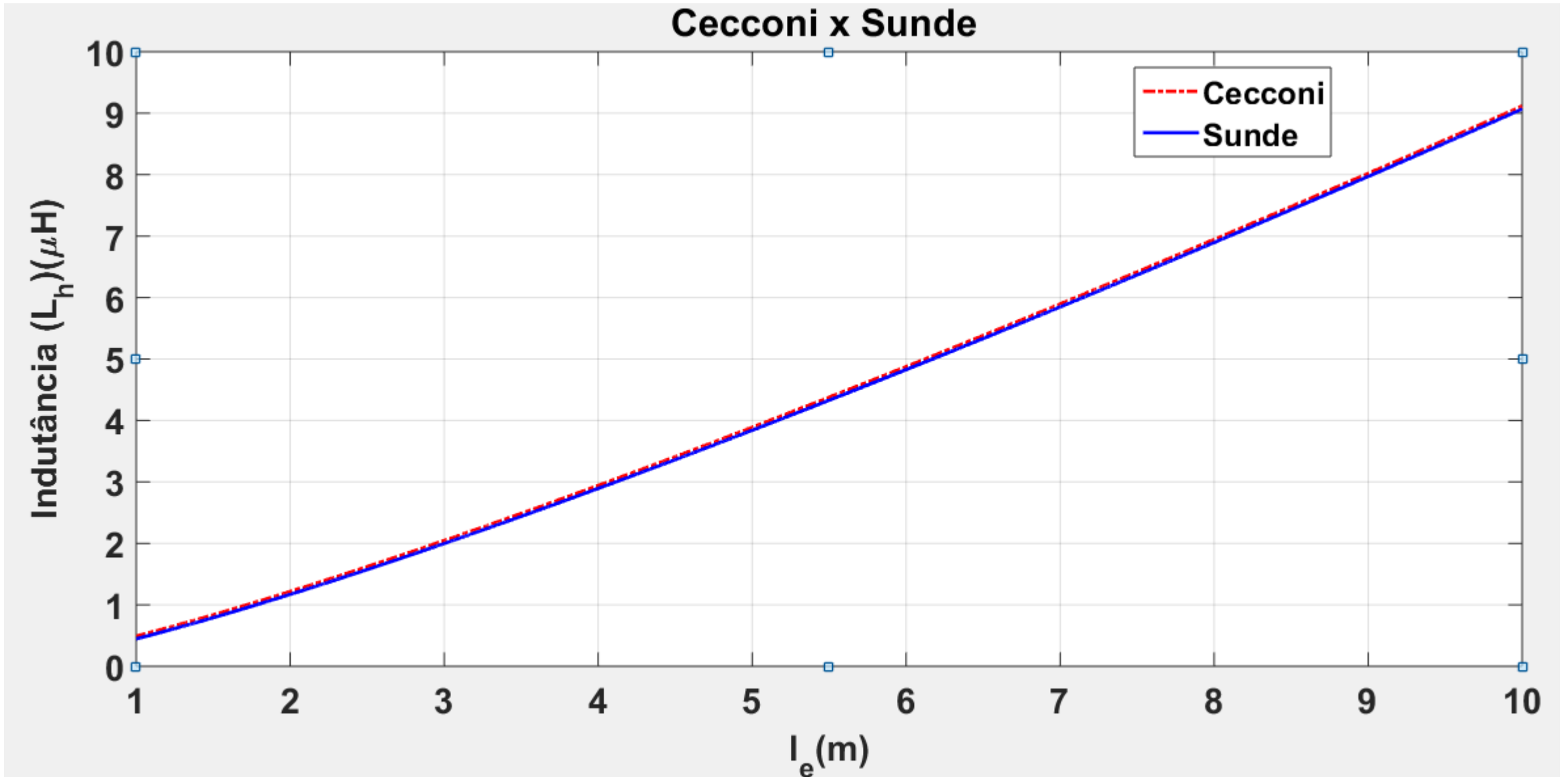
# Variação dos parâmetros (Cecconi x Sunde)



# Variação dos parâmetros (Cecconi x Sunde)

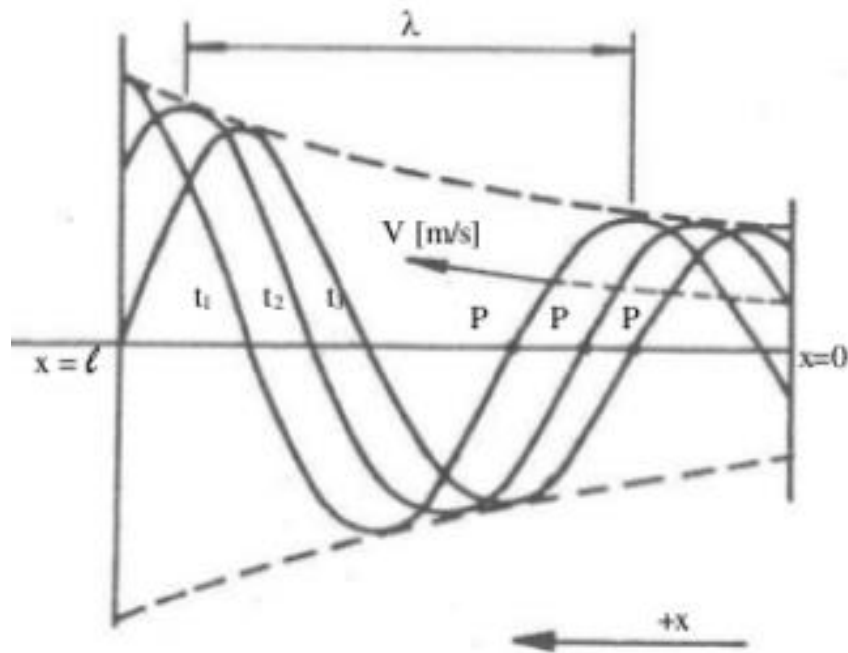


# Variação dos parâmetros (Cecconi x Sunde)



# Critério para escolher ( $l_e$ )

Função de propagação de um meio (m)



$$\gamma = \sqrt{j2\pi f\mu_m(1/\rho_m + j2\pi f\epsilon_m)} = \alpha + j\beta;$$

$$\sigma_m = 1/\rho_m \quad \lambda = \frac{2\pi}{\beta};$$

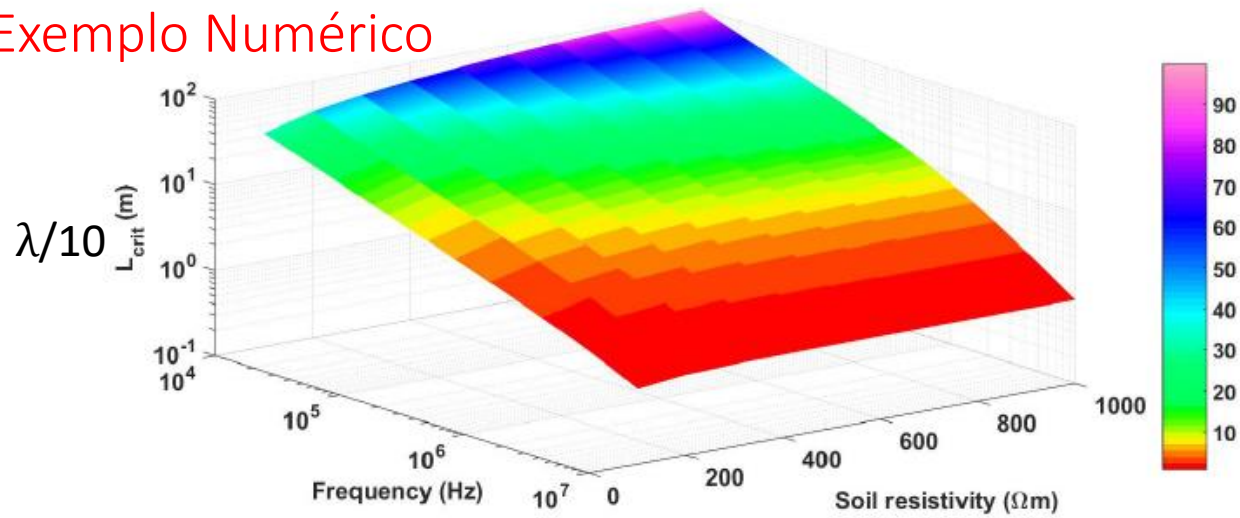
$$\beta = \omega \sqrt{\frac{\mu_m\epsilon_m}{2} \left[ \sqrt{1 + \left(\frac{\sigma_m}{\omega\epsilon_m}\right)^2} + 1 \right]}$$

$$L_{crit} = \lambda/10;$$

$$2a_h/10 \leq l_e \leq L_{crit}$$

Se essa condição é satisfeita, pode-se representar um eletrodo por uma cascata de N-circuitos pi.

## Exemplo Numérico



Raio = 12,5 mm,  $d = 0,5$ ,  $L = 30$  m, solo de  $\rho_m = 500$  Ohmm,  $\epsilon_m = 10\epsilon_0$ ,  $\mu_m = \mu_0$ .

Freq. Máx. Do sinal de entrada: 10 MHz

1)-Cálculo da função de propagação

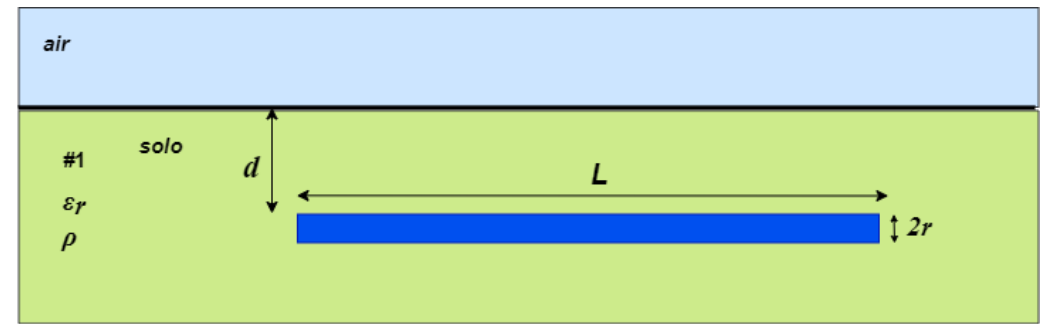
$$\gamma = \sqrt{\left( j2\pi 10^7 4\pi 10^{-7} \left( \frac{1}{500} + j2\pi 10^7 10 \cdot 8.8510^{-12} \right) \right)} = \alpha + j\beta = 0,1173 + j0,6731$$

2)-Cálculo de Lambda  $\lambda = \frac{2\pi}{\beta} = 9,3353$

3)-Cálculo de Lcrit:  $L_{crit} = \lambda/10 = 0,93353$

4)-Cálculo do comprimento elementar  $l_e = \frac{L}{N} = 30/N$

5)-Escolha de 3 valores para N: 5, 10 e 100 pis  
 $l_e = 6$ ; 3 e 0.3 m

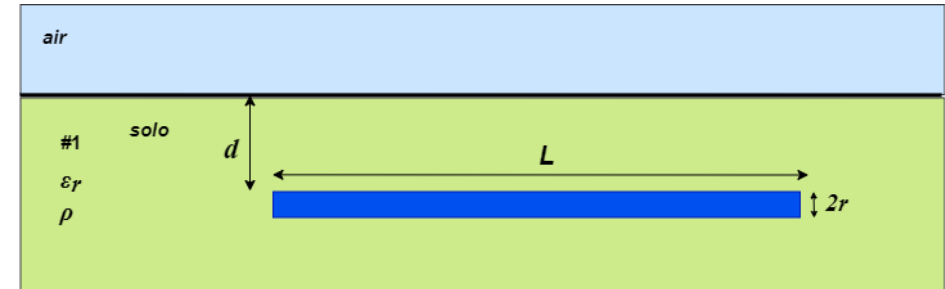
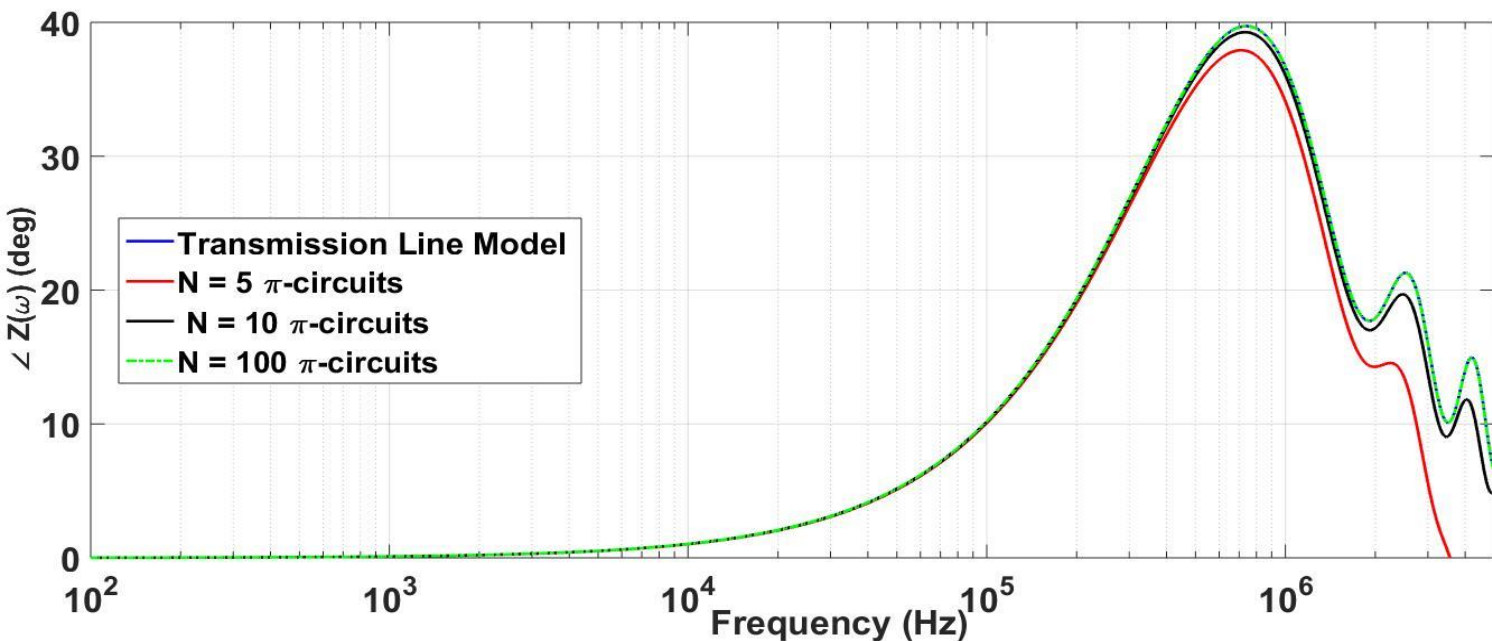
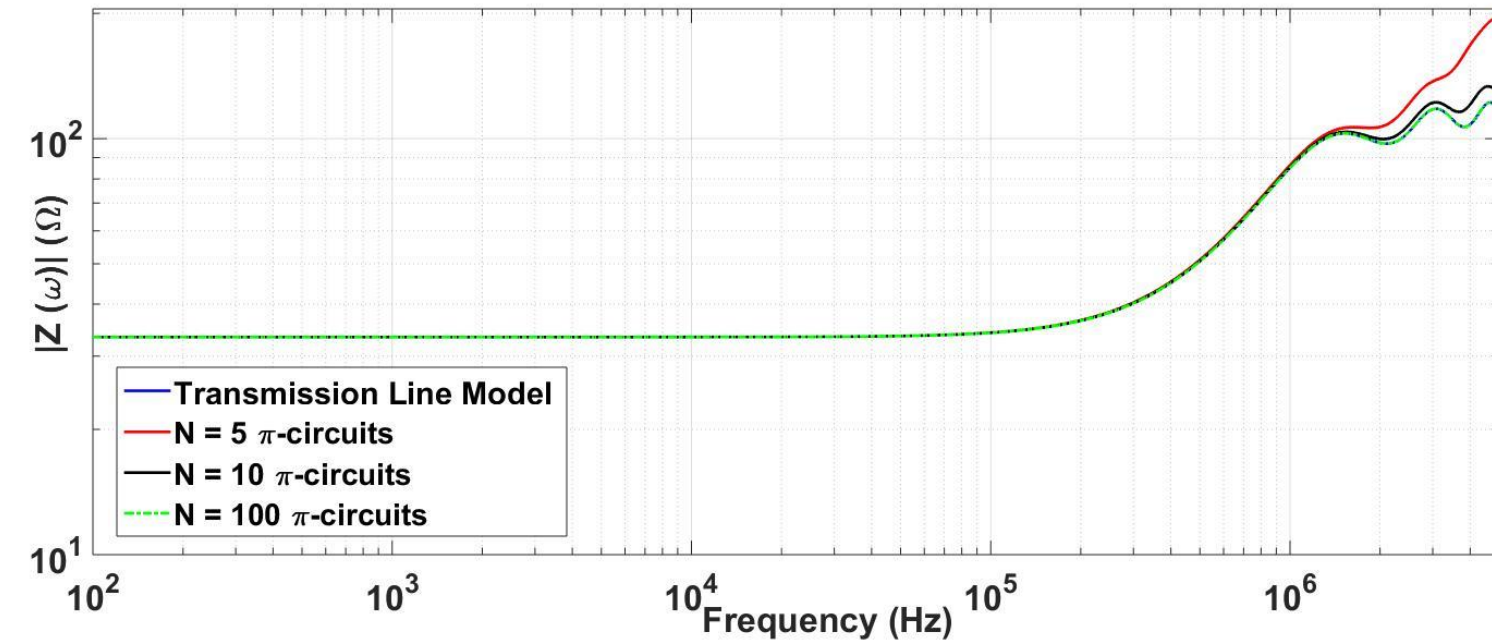


```
clear all ; close all ; clc;
|
%dados geometricos do eletrodo
L = 30; %comprimento do eletrodo
N = 100;% numero de circuitos pi
le= L/N; % comprimento elementar
%dados gerais do meio
pm=500; %resistividade meio
sm=1/pm; % condutividade do meio
er=10; %permissividade relativa
e0=8.854e-12; %permissividade vácuo
em=er*e0; %permissividade meio
u0=4e-7*pi; %permeabilidade vácuo
ur=1; %permeabilidade relativa
um=u0*ur; %permeabilidade do meio
fmax= 10e6;% frequência maxima do sinal de entrada
w=2*pi*fmax;% frequência angular
gama=sqrt((i*w*um)*(sm+i*w*em))
alfa= real(gama)% constante de atenuação
beta=imag(gama)% constante de fase
lambda=2*pi/beta % comprimento de onda
Lcrit=lambda/10 % comprimento critico
```

# Influência de N

$l_e = 6; 3 \text{ e } 0.3 \text{ m}$

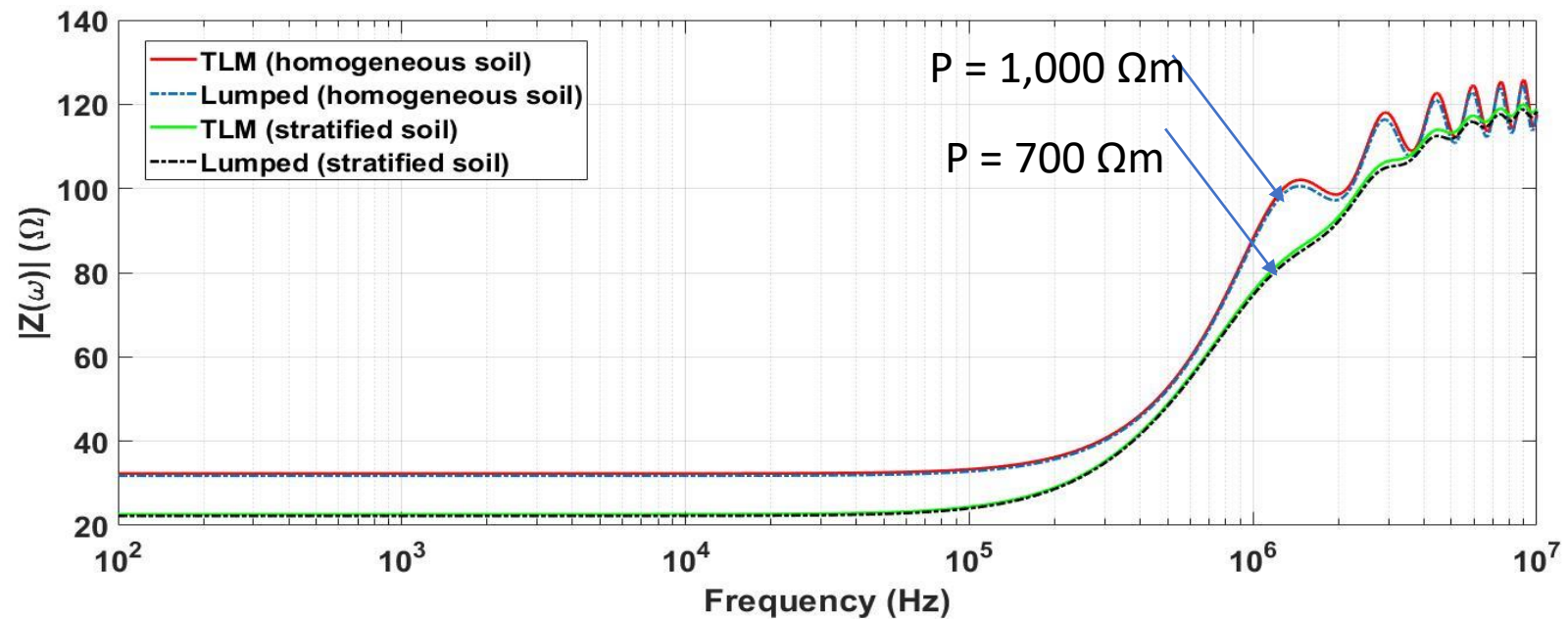
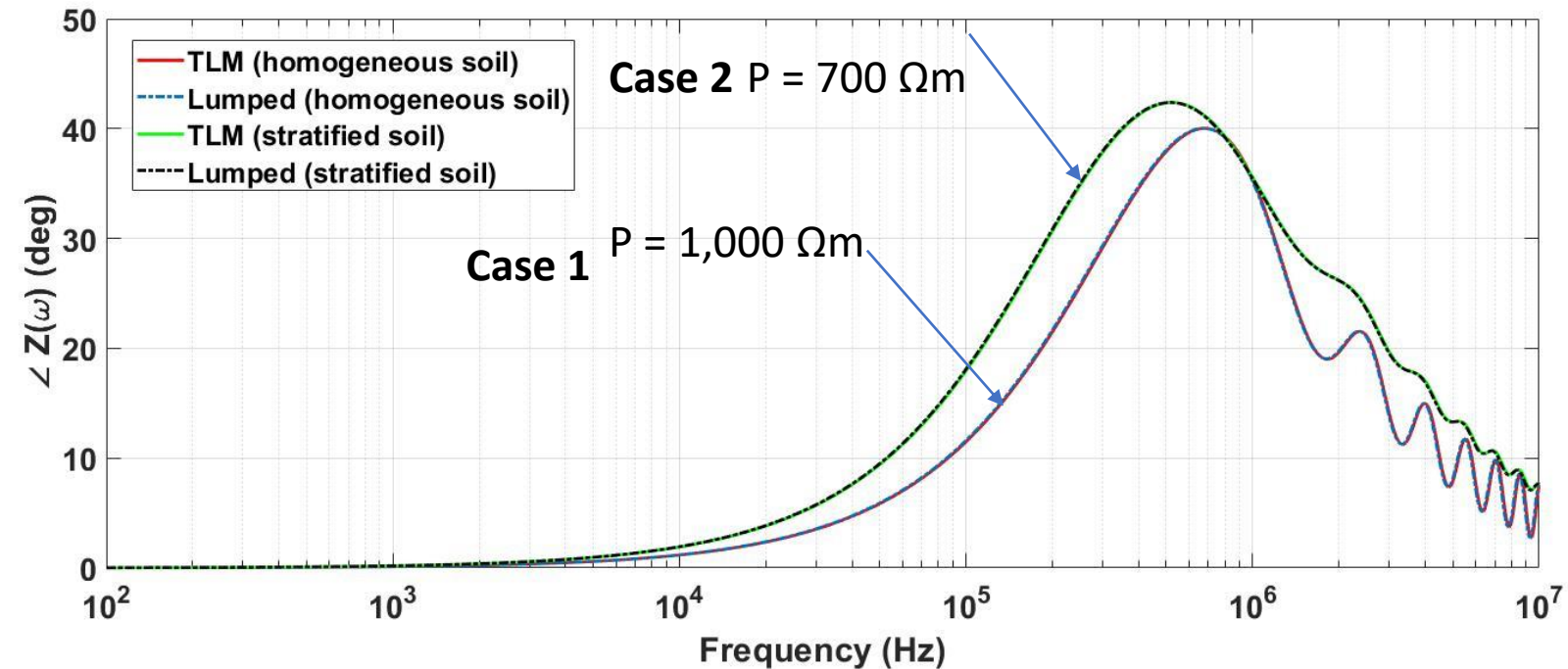
Verifica-se que somente quando  $N = 100$  tem-se que a condição (\*) é satisfeita e o eletrodo é adequadamente representado pelo circuito pi.



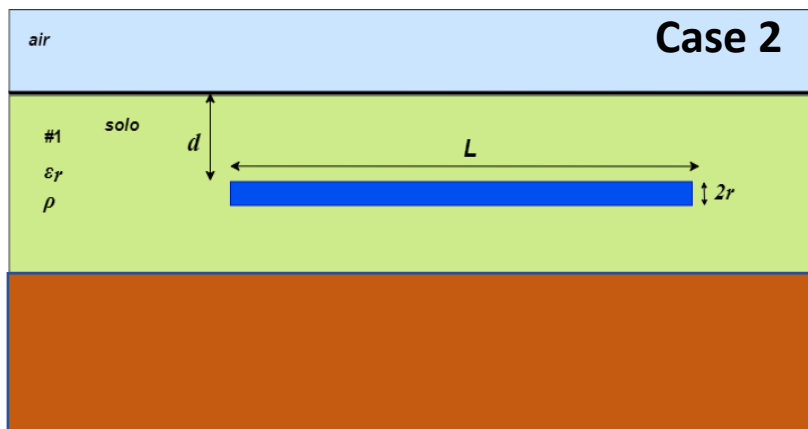
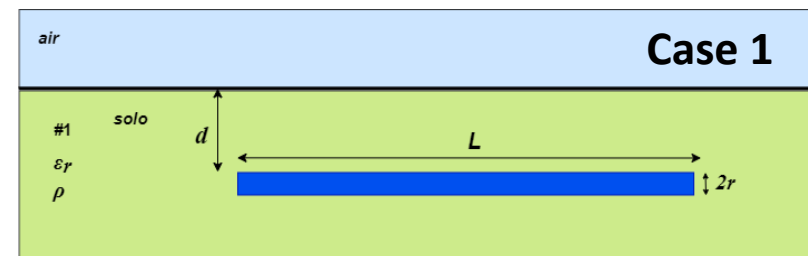
$$L_h = \frac{\mu_0 l_e}{4\pi} \left[ \ln \frac{2l_e}{r_h} + \ln \frac{l_e}{d} - 2 + \frac{2d}{l_e} - \frac{d^2}{l_e^2} + \frac{1}{2} \frac{d^4}{l_e^4} \right];$$

$$C_h = \frac{\mu_0 \epsilon_0 \epsilon_r l_e^2}{2L_h}; \quad G_h = \frac{C_h}{\rho_s \epsilon_0 \epsilon_r}; \quad R_h = \frac{\rho_c}{\pi r_h^2}$$





$N = 100$  pis

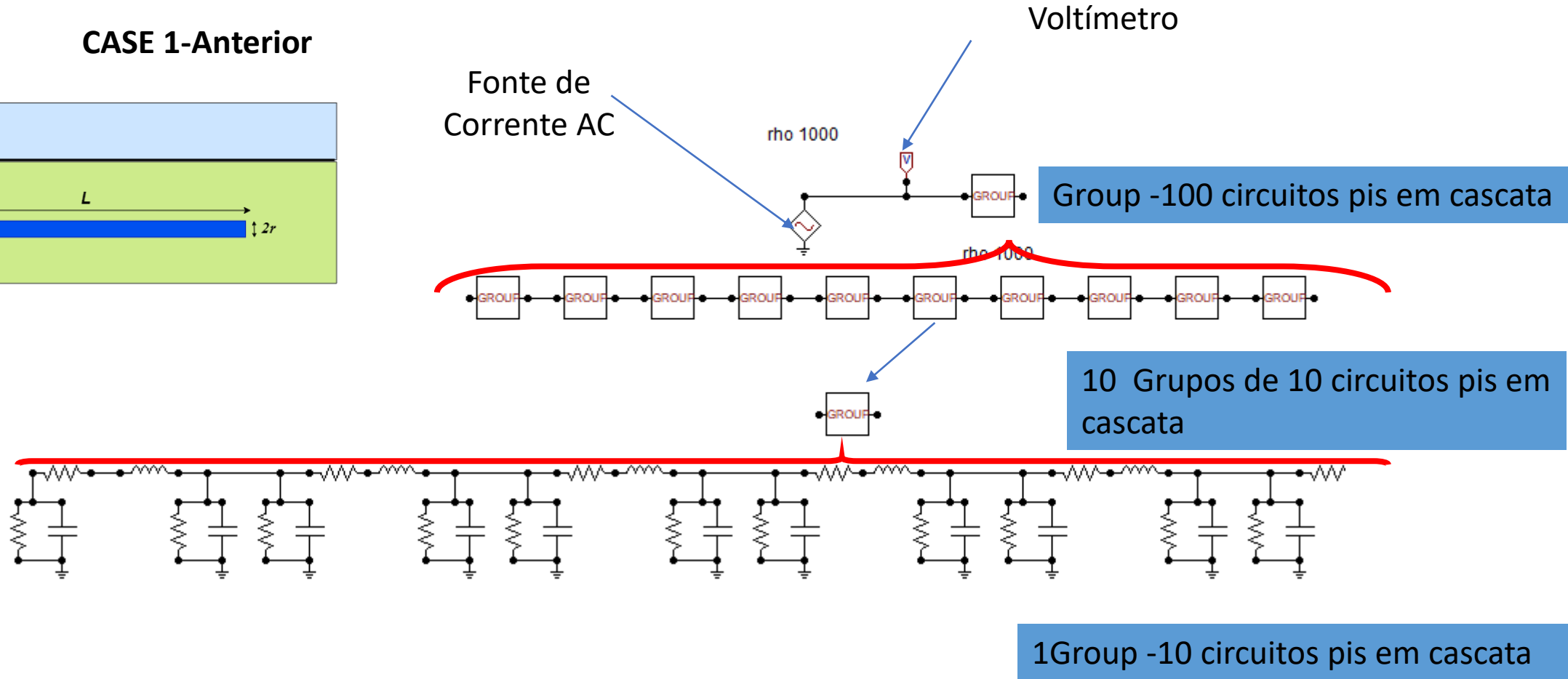
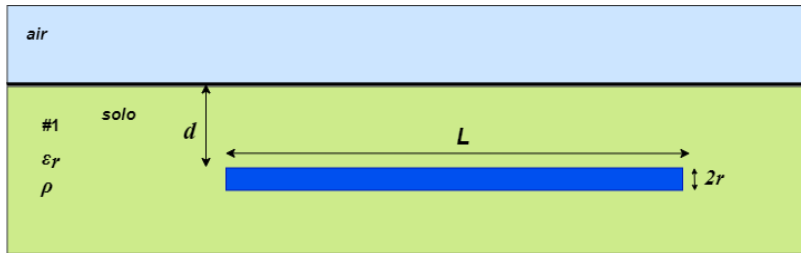


$L = 31,5$  m;  $d = 0,70$ ;  $r = 15.87$  m  
 $L_{cri} = 1$  m (aprox);  $l_e = 31,5/100$

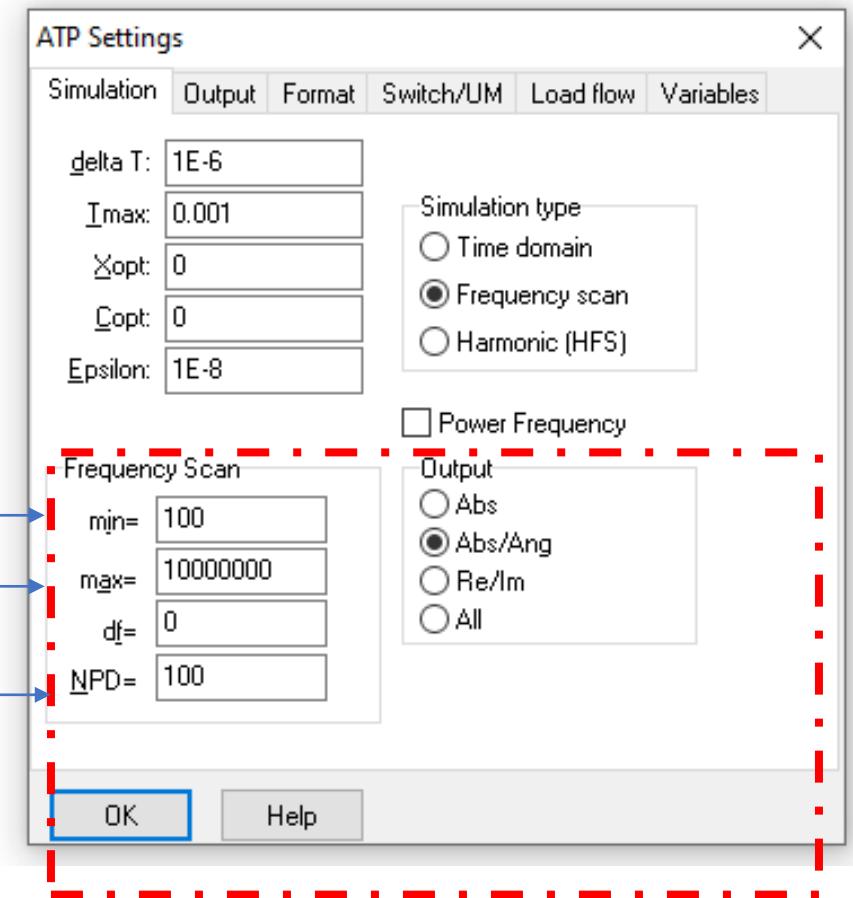
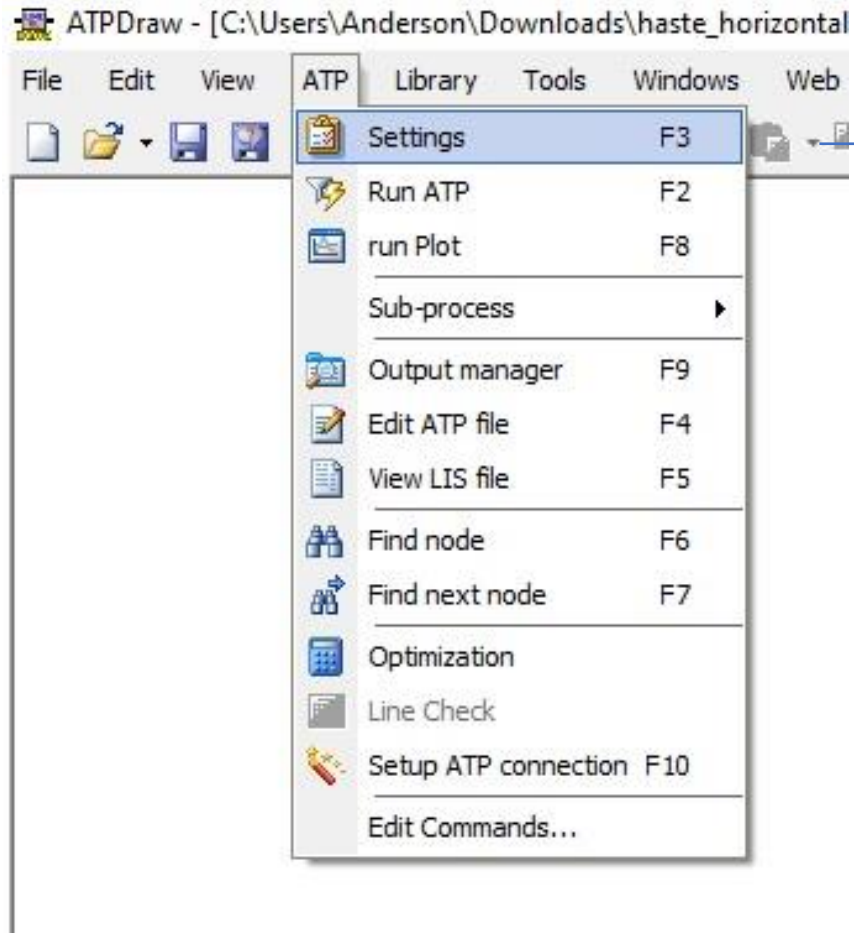
Case 1:  $p_1 = 1,000$  Ohm;  
 Case 2:  $p_1 = 1,000$  Ohm;  $p_2 = 500$  Ohmm

# Simulação no ATP

CASE 1-Anterior



# Resposta em freq. no ATP



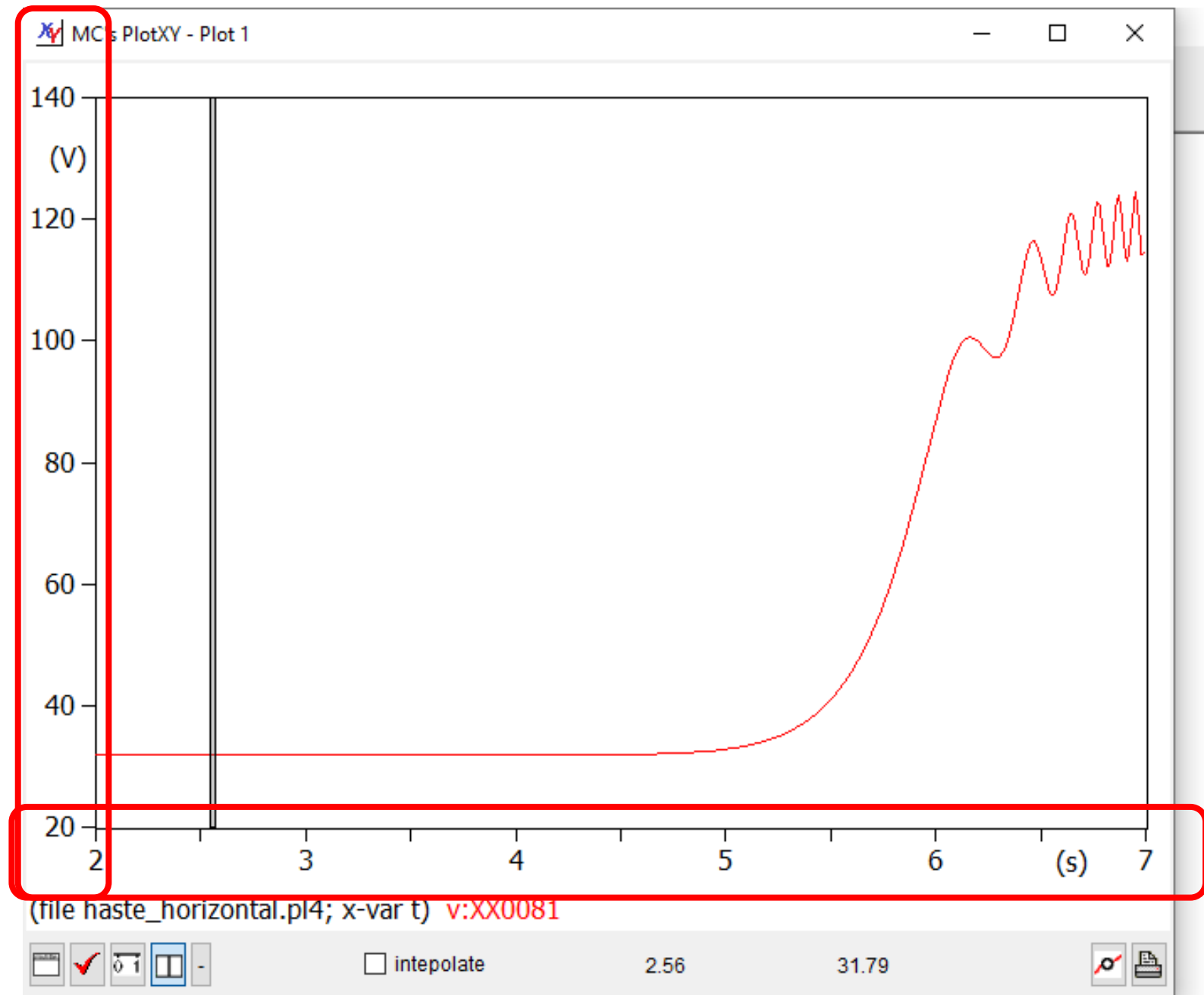
Número de pontos por década

# Run Plot

Magnitude da Impedância

Atenção

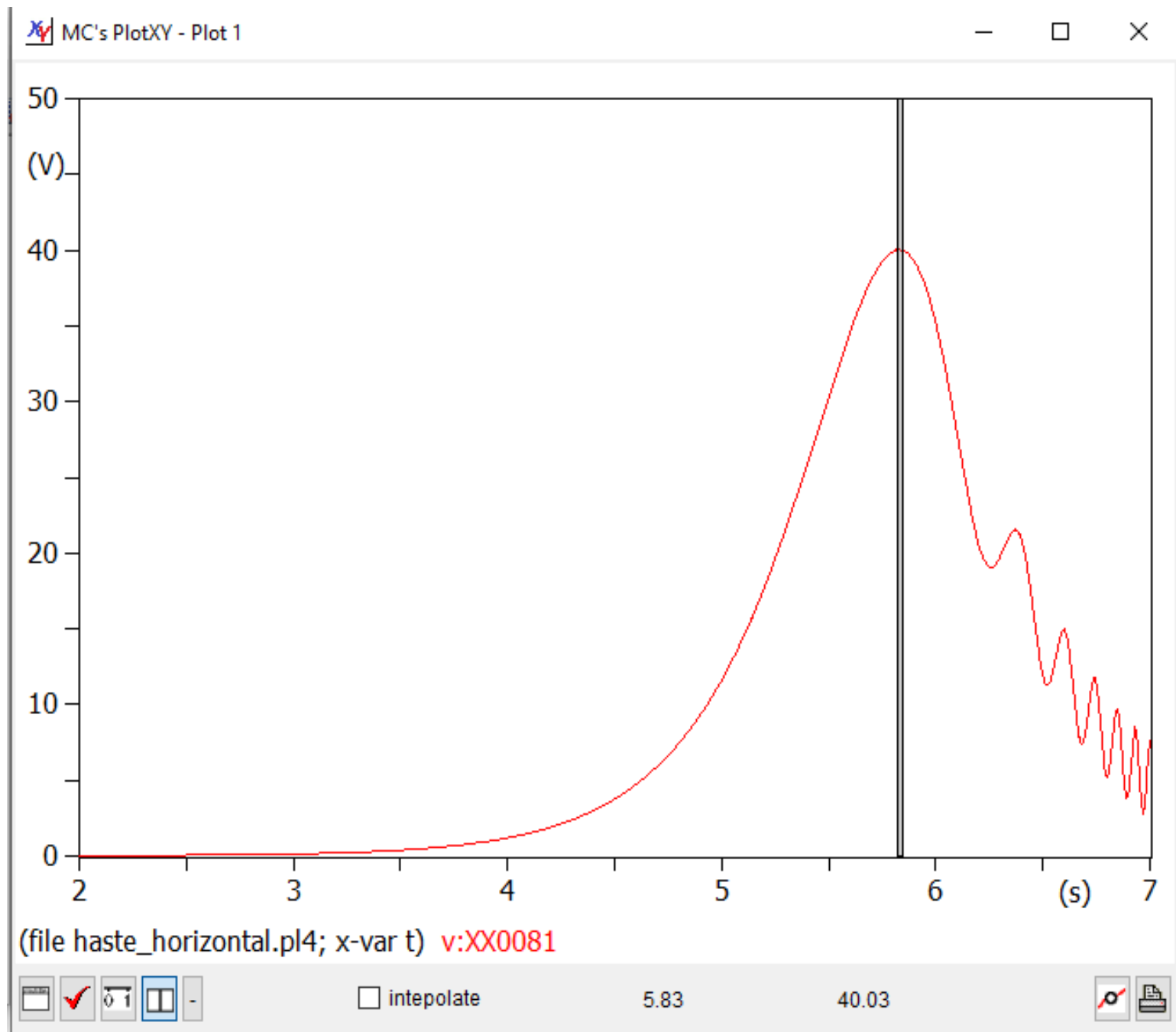
Eixo em Volts e segundos, porém  
Nesse caso são a Magnitude (Ohm)  
e a Freq(Hz)!!!



## Fase da Impedância

### Atenção

Eixo em Volts e segundos, porém  
Nesse caso são a Fase (graus) e a  
Freq(Hz)!!!



# Alternativa-Plotar no Matlab

The image shows two overlapping windows from the MATLAB software. The left window is titled "MC's PlotXY - Data selection" and displays a table of data files and a variable selection interface. The right window is titled "Save File" and shows a file explorer view of the "Área de Trabalho" (Desktop) with a file type dropdown menu open.

**MC's PlotXY - Data selection window:**

	f	FileName	# of vars	# of Points	Tmax
x	1	haste_horizontal.pl4	3	501	7

	f	#	Variable name	X
1	t			
2	v:XX0081			
3	v:XX0081			

Below the table, the variable "v:XX0081" is selected for plot1. The interface includes buttons for "Fourier", "Plot", "Save vars", and "Reset". At the bottom, there are options to "Equalise plot window sizes" with radio buttons for "to Plot win 1" and "to:" followed by input fields, and buttons for "Equate" and "Arrange".

**Save File dialog window:**

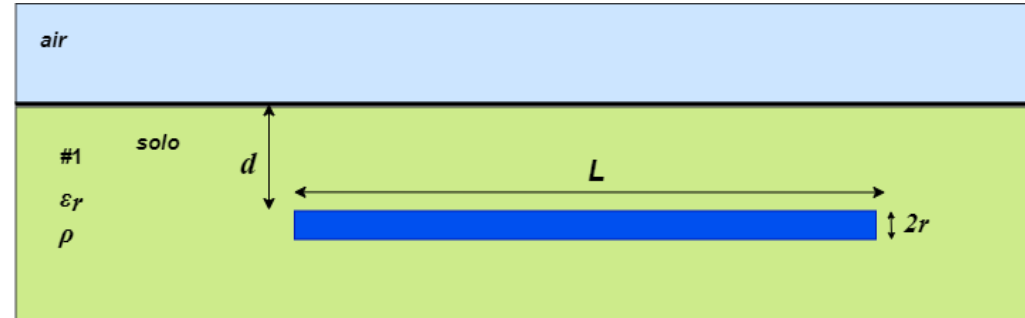
The dialog shows the file name "impedancia" and the file type dropdown menu is open, listing the following options:

- ADF (\*.adf)
- ADF (\*.adf)
- MATLAB (\*.mat)
- PL4 (\*.pl4)

# Exercício

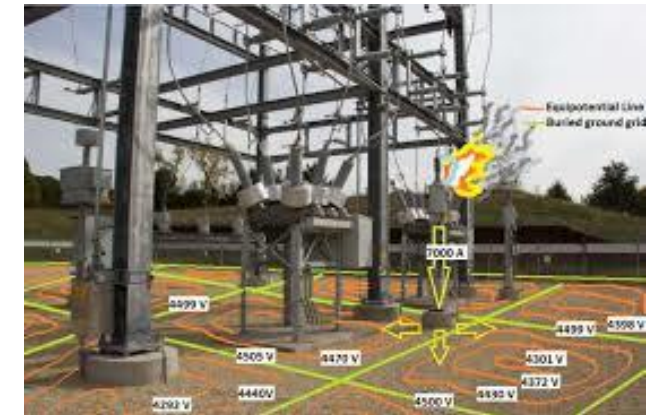
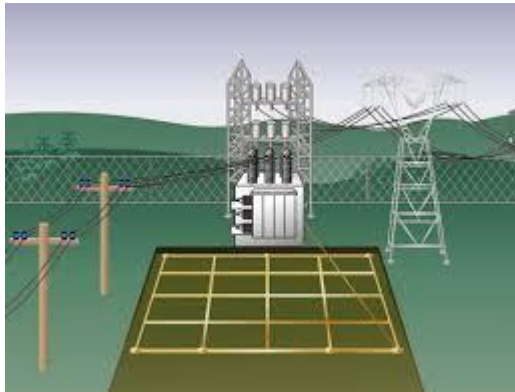
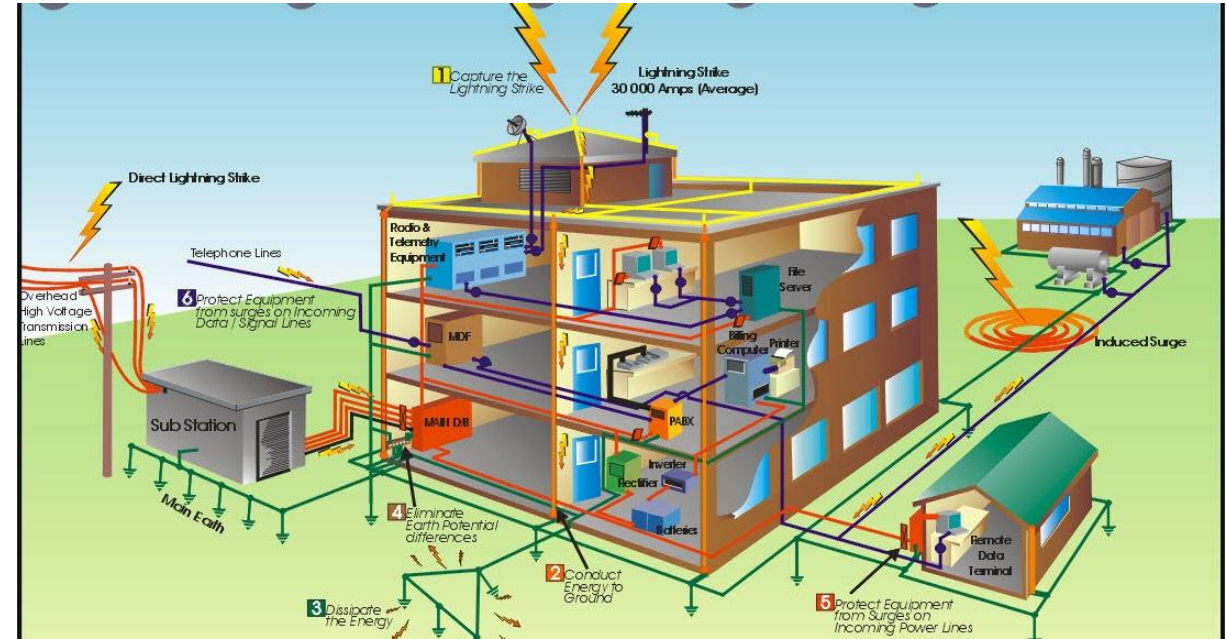
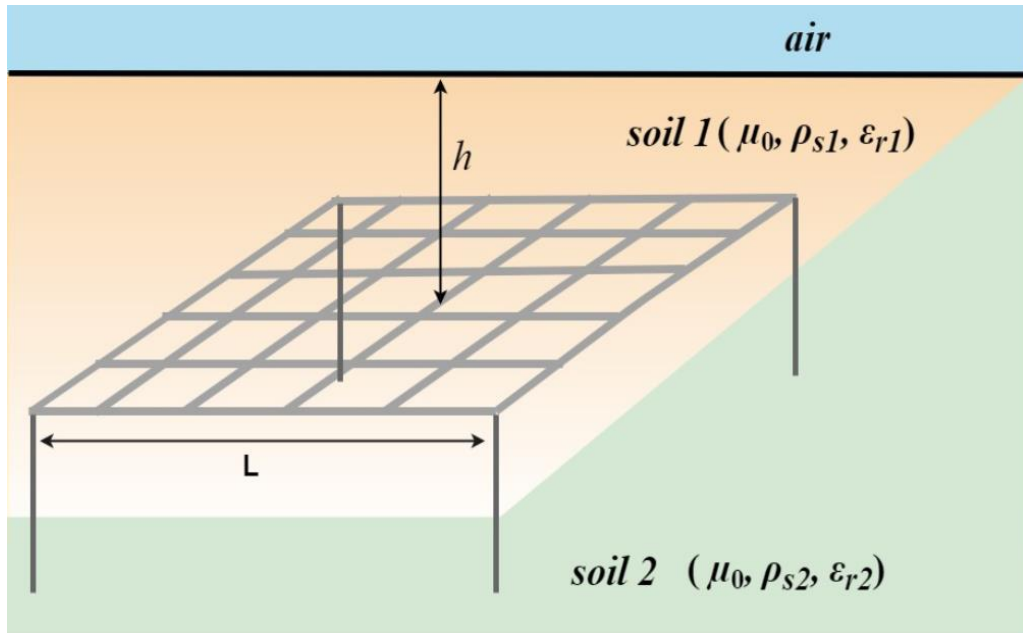
Um eletrodo horizontal de cobre de 15 m de comprimento e raio 12 mm está enterrado a uma profundidade de 0,6 m em um solo de 70 Ohmm, permissividade relativa de 15, permeabilidade relativa de 1. Considerar a frequência máxima de 1 MHz. Calcule o comprimento de onda para esse meio (solo), o comprimento crítico ( $L_{crit}$ ), o comprimento elementar ( $l_e$ ) e os parâmetros elétricos usando a equação propostas por Cecconi.

Obs: Várias repostas para são possíveis para  $l_e$  e consequentemente para os parâmetros elétricos.



$$L_h = \frac{\mu_0 l_e}{4\pi} \left[ \ln \frac{2l_e}{r_h} + \ln \frac{l_e}{d} - 2 + \frac{2d}{l_e} - \frac{d^2}{l_e^2} + \frac{1}{2} \frac{d^4}{l_e^4} \right];$$
$$C_h = \frac{\mu_0 \epsilon_0 \epsilon_r l_e^2}{2L_h}; \quad G_h = \frac{C_h}{\rho_s \epsilon_0 \epsilon_r}; \quad R_h = \frac{\rho_c}{\pi r_h^2}$$

# Malhas de Aterramento





# Finalidades

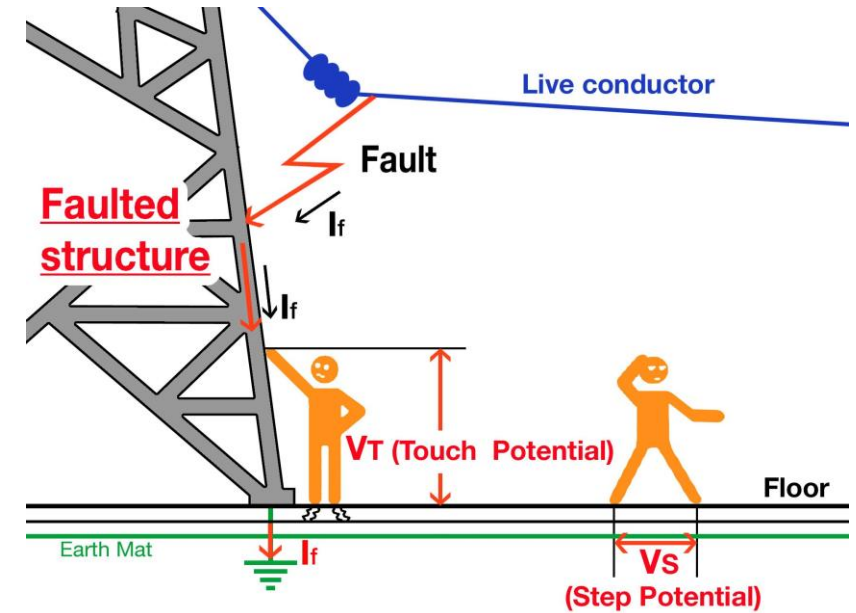
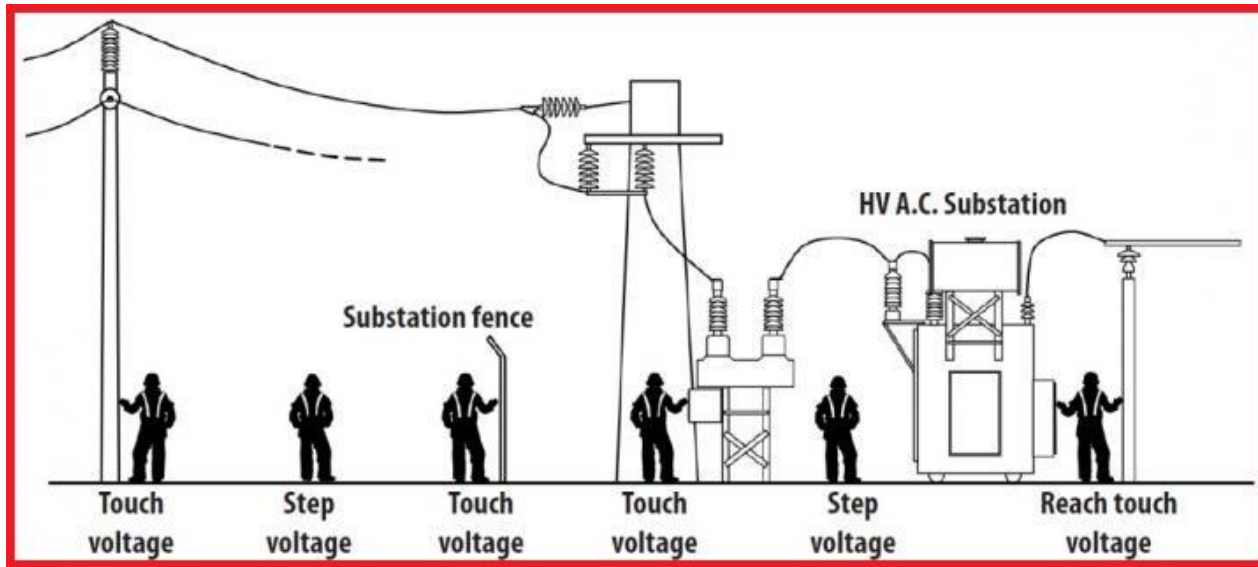
Malhas de aterramento (MAs) desempenham um papel fundamental na continuidade e na operação confiável de um sistema de energia elétrica. MAs devem fornecer um caminho de baixa impedância para altas correntes causadas por faltas à terra ou pelas descargas atmosféricas incidentes em linhas de transmissão que devem ser escoadas para o solo.

MAs são projetadas para minimizar as tensões de passo e toque visando à segurança de pessoas e a proteção dos equipamentos nas subestações elétricas e em plantas industriais.

Na literatura científica, pesquisadores propõem diversos modelos para computar a impedância de uma MA baseados em:

- (i) fórmulas analíticas;
- (ii) modelagem por parâmetros concentrados ou distribuídos usando a teoria de circuitos ou
- (iii) por métodos numéricos empregados na resolução das equações de Maxwell, tais como o Método dos Momentos (MoM) Método dos Elementos Finitos (MEF)
- (iv) modelos híbridos, que combinam a teoria de circuitos e os métodos numéricos, tais como o Partial Element Equivalent Circuit (PEEC).

# Tensão de passo e toque



# Composição

As MAs são constituídas por um grande reticulado de eletrodos horizontais (EHs) enterrados a uma dada profundidade e que são interligados por juntas mecânicas ou soldas em suas conexões cruzadas (nós).

Adicionalmente, diversos eletrodos verticais (VEs) (hastes) são inseridos nesses nós ou ao longo do contorno da malha de modo a se obter a impedância mais baixa possível, o que resulta em uma área considerável do terreno

Diversos aspectos devem ser levados em consideração para se calcular com precisão a impedância de aterramento das MAs, tais como:

- Solos estratificados;
- Variação dos parâmetros elétricos do solo (resistividade e permissividade) com a frequência,
- Acoplamento mútuo entre os condutores,
- Ionização do solo,
- o arranjo dos condutores na malha;
- Tipo de distúrbio que origina o transitório eletromagnético.

# Conexões das malhas e interligações



# Comportamento Elétrico de Malhas

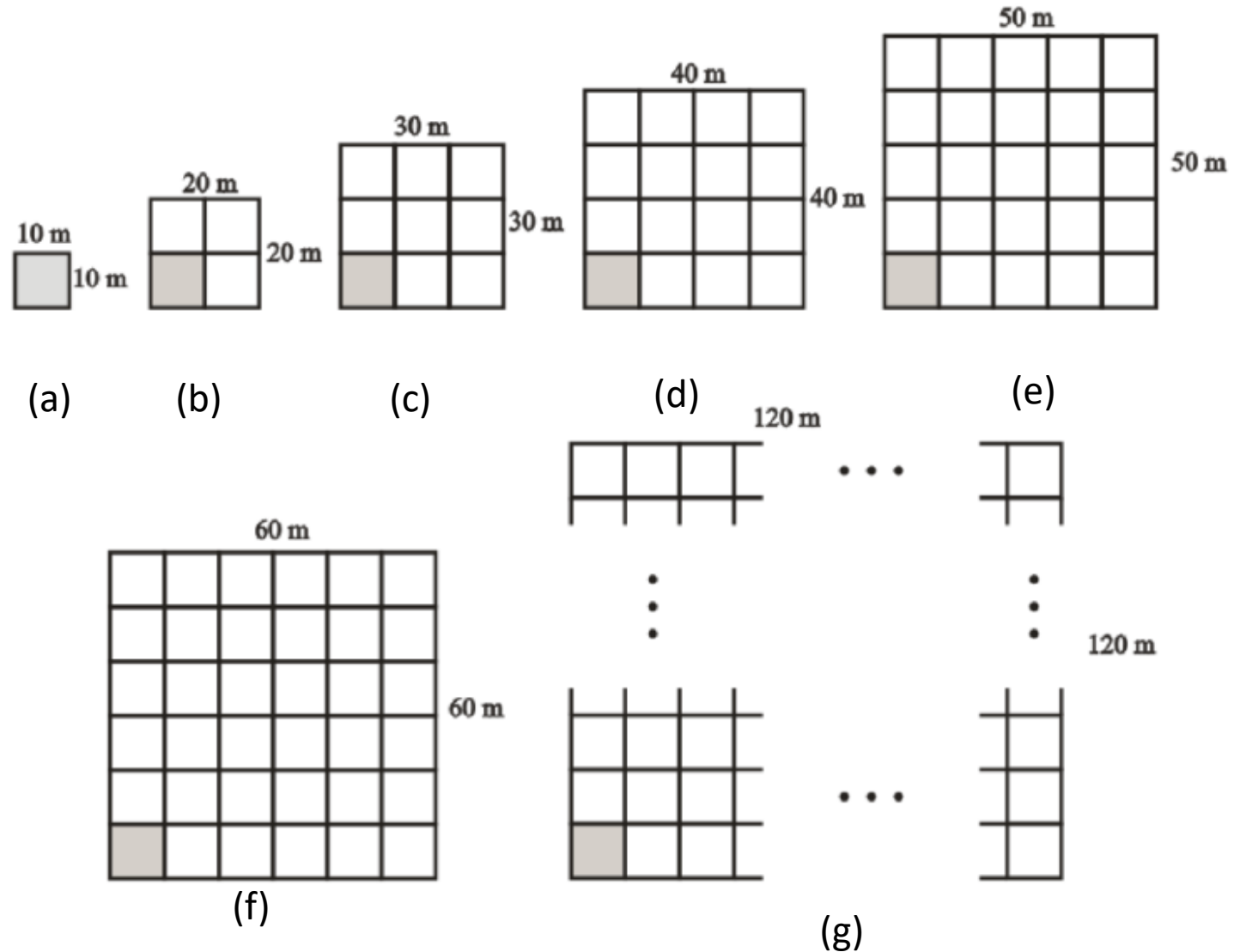
- Sabe-se que o comportamento elétrico de uma MA submetida a um fenômeno de baixa frequência, como uma falta, é bem diferente frente a uma descarga atmosférica, que possui um espectro de frequência da ordem de MHz
- Isso ocorre devido aos comportamentos indutivos e capacitivos próprios e mútuos entre os condutores e sua interação com o solo serem expressivos nas altas frequências, enquanto que esses comportamentos são desprezados nas baixas frequências onde a MA é vista apenas como uma resistência equivalente.

# Cálculo da Imp. De Malhas x Frequências

UMA PROPOSTA DE REPRESENTAÇÃO DE SISTEMAS DE ATERRAMENTO  
DIRETAMENTE NO DOMÍNIO DO TEMPO

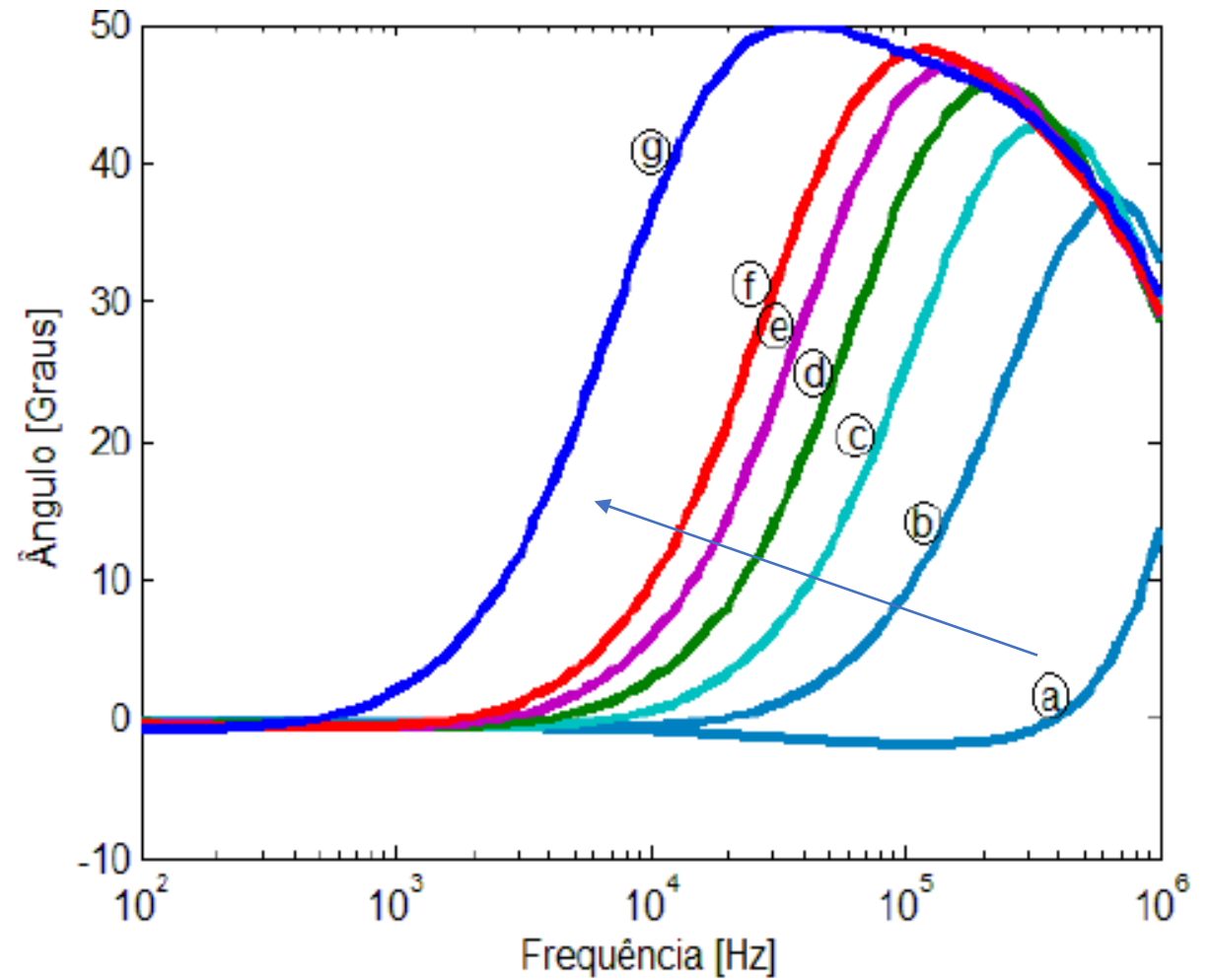
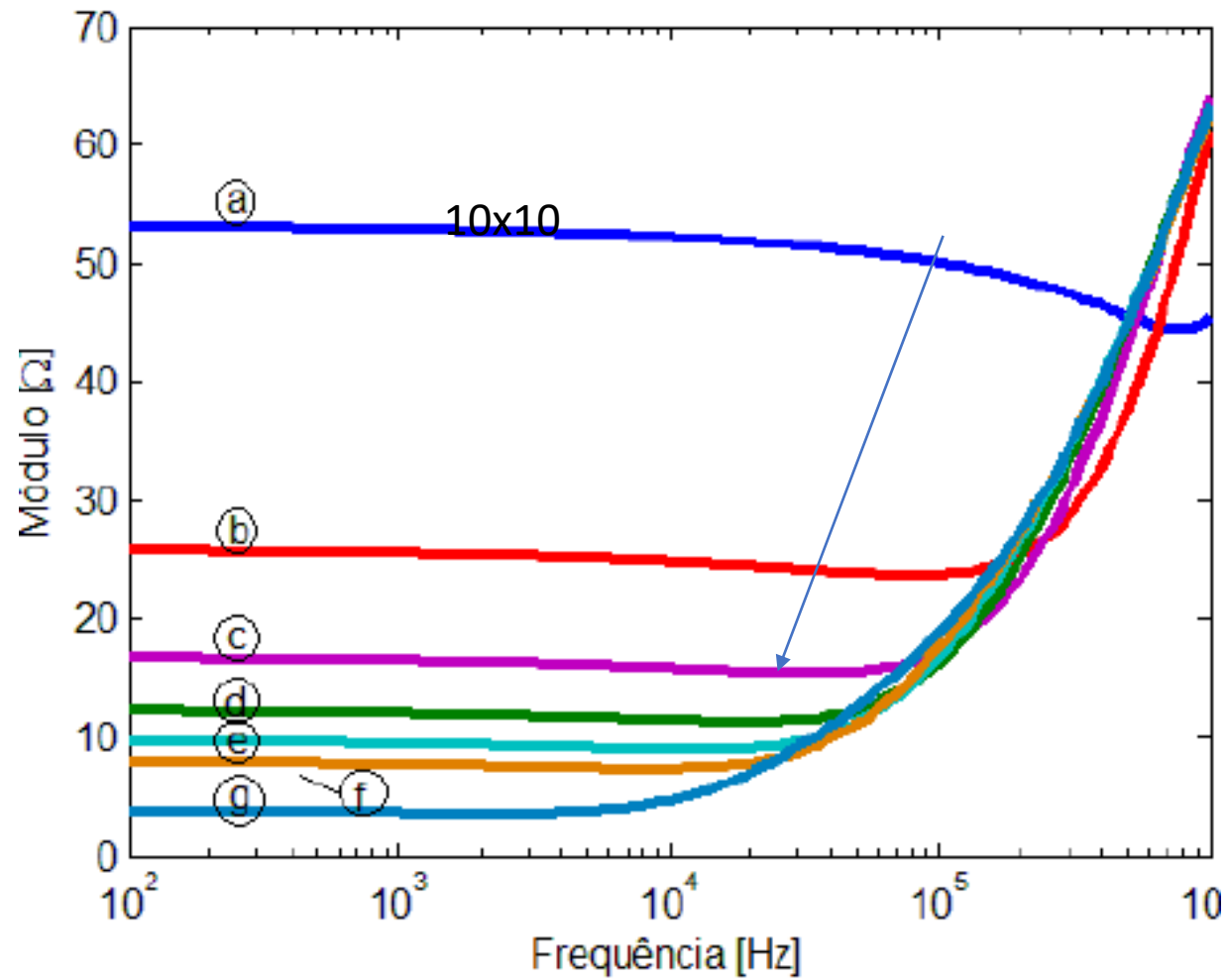
CLAUDINER MENDES DE SEIXAS

Impedância Calculado pelo MoM via  
Matlab

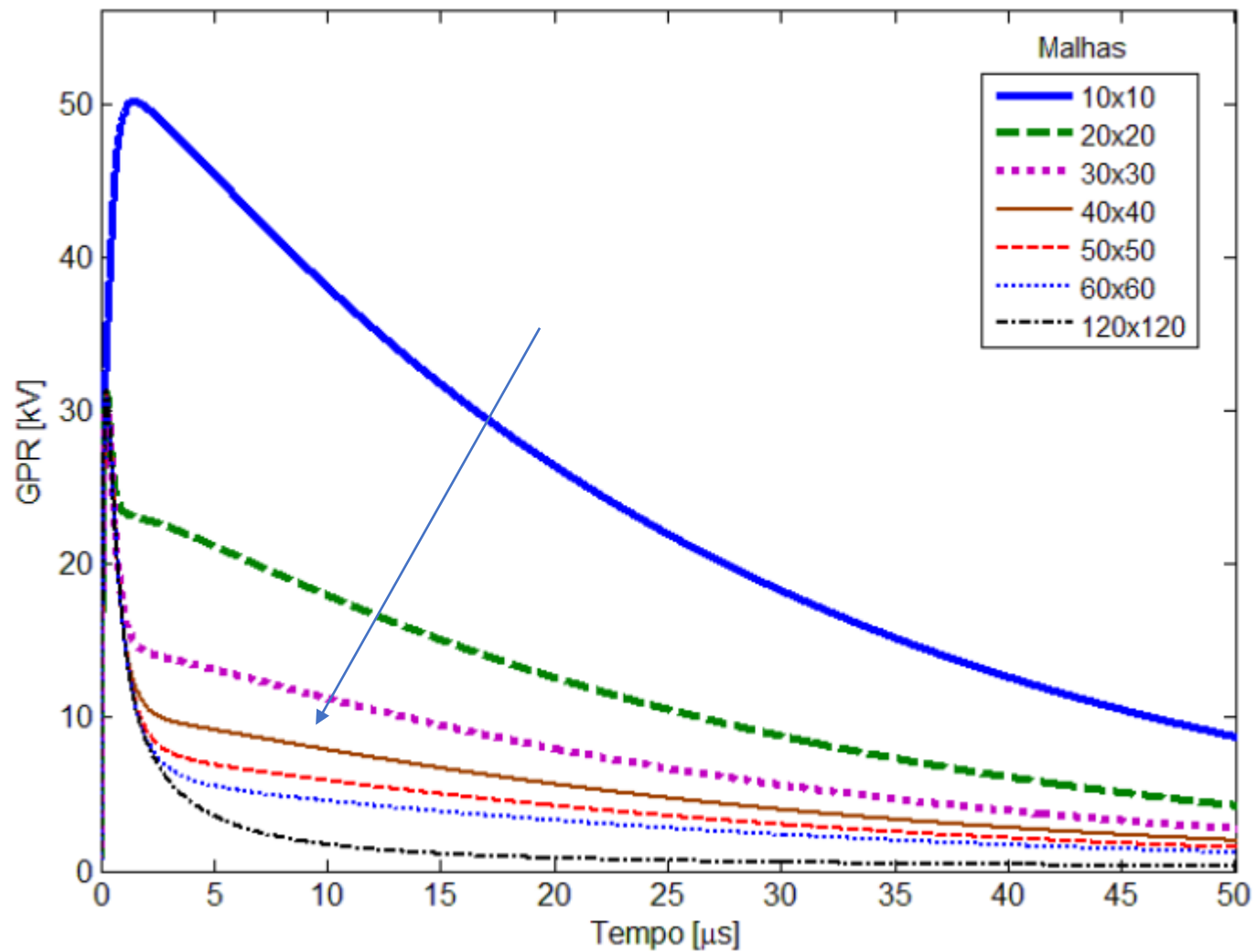


Nas simulações foram considerados os mesmos dados de entrada que em Grcev e Heimbach (1997), isto é, eletrodos de cobre (resistividade igual a  $1,724 \times 10^8 \Omega\text{m}$ ) com raio de  $7 \times 10^{-3}$  m, enterrados a uma profundidade de 0,5 m, em solo de resistividade elétrica de  $1000 \Omega\text{m}$  e permissividade elétricas relativa igual a 9.

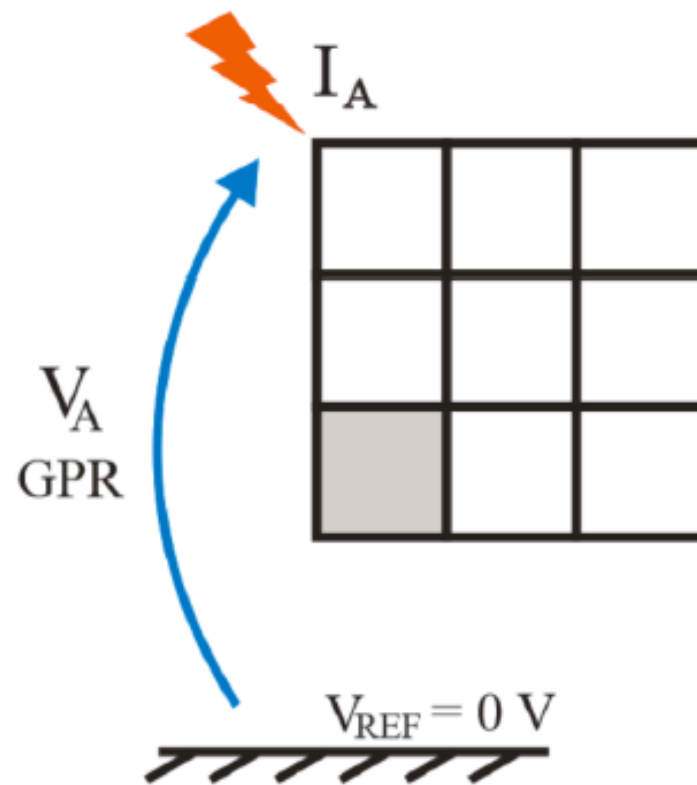
# Impedância de Malhas



# GPR



Descarga atmosférica 1,2/20 us

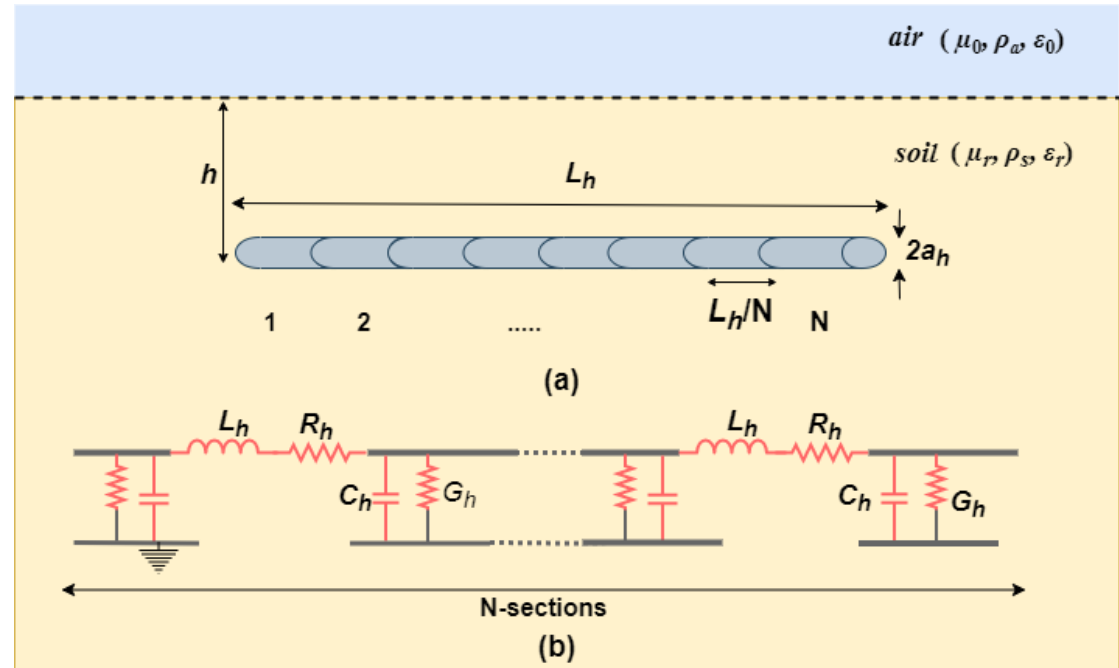
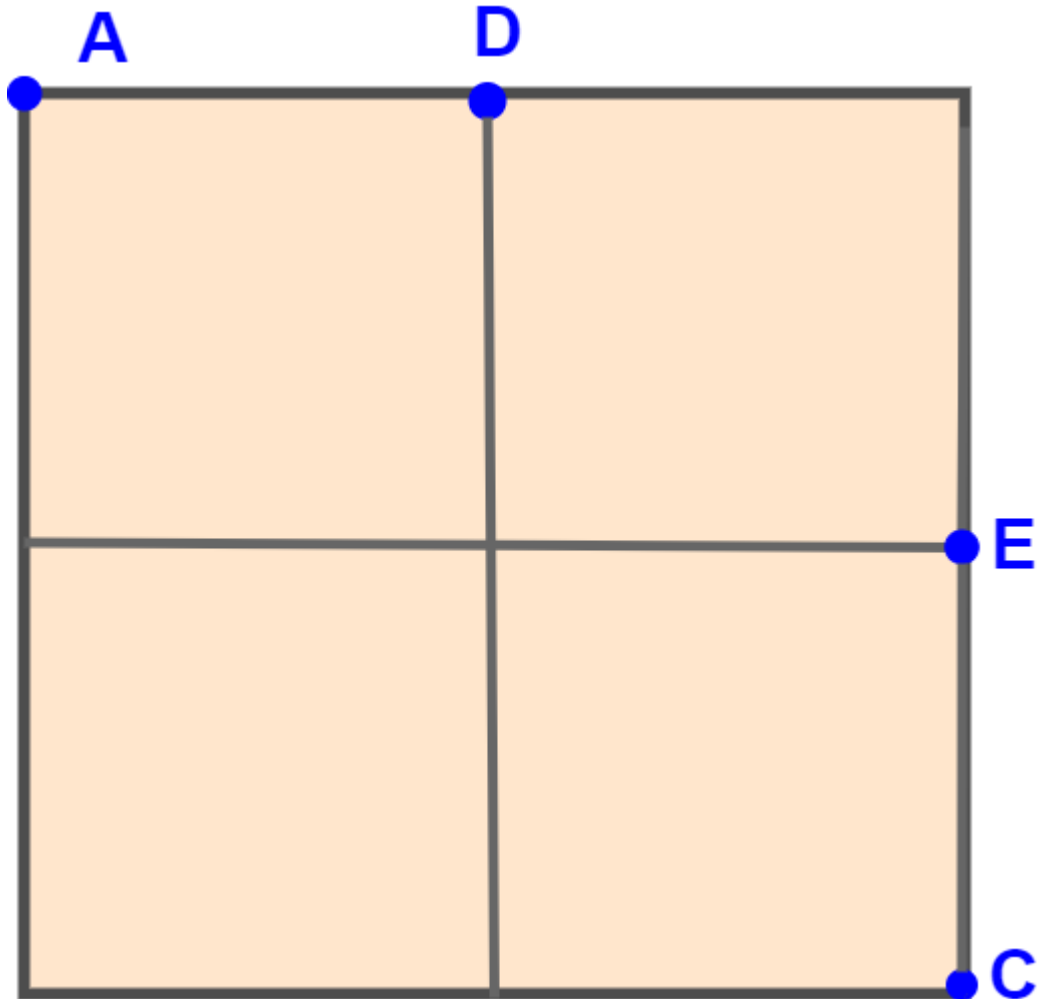




Considerando os eletrodos horizontais e as hastes verticais são modelados por diversos modelos propostos na literatura visando calcular as suas impedâncias de aterramento desses condutores em solos homogêneos/estratificados, tais como:

- (i) modelos a parâmetros distribuídos usando a teoria de Linhas de Transmissão;
- (ii) modelos a parâmetros concentrados utilizando a Teoria eletromagnética Vector Fitting;
- (iii) Métodos Numéricos MoM, FEM, FDTD.

# Abordagem a parâmetros concentrados



The studied grid electrode is a 4-meshe grid with dimensions of 12m x 12m, made of copper conductors of  $r=7\text{mm}$  radius and it is buried at a depth of  $d = 0,6\text{m}$  in a soil with  $\rho = 100 \Omega\text{m}$ ,  $\varepsilon_r = 36$  and  $\mu_r = 1$ . The electrode is excited, in point A of fig.2, by a lightning current:

$$i_2(t) = 10 \cdot (e^{-14300t} - e^{-5400000t}) \text{ kA.}$$

For the grid electrode the propagation constant has the value:

$$\hat{\gamma} = \sqrt{j2\pi \cdot f_x \mu_0 \mu_r (\sigma + j2\pi \cdot f_x \varepsilon_0 \varepsilon_r)} \Rightarrow$$

$$\Rightarrow \sqrt{j2\pi \cdot 10^7 \cdot 1,256 \cdot 10^{-6} \cdot 1 \cdot (0,01 + j \cdot 2\pi \cdot 10^7 \cdot 8,854 \cdot 10^{-12} \cdot 36)} =$$

$$= 0,3 + j1,3$$

The phase constant  $\beta_2$  is equal to 1,3 rad/m so the wave length has the value:

$$\lambda = \frac{2\pi}{1,3} = 4,83\text{m}$$

so the length,  $l$ , of an elementary cell is chosen:

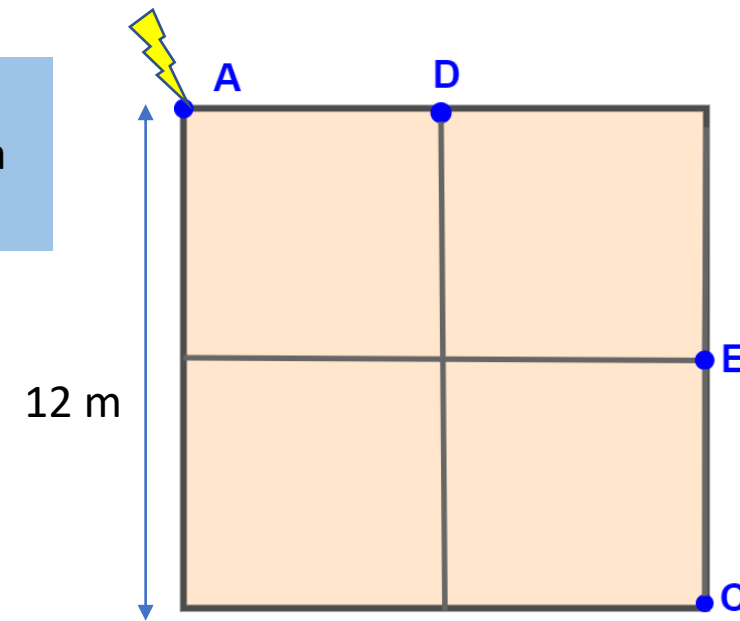
$$l = 0,24\text{m} < \frac{\lambda}{10} = 0,483\text{m}$$

$$L_h = \frac{\mu_0 l_e}{4\pi} \left[ \ln \frac{2l_e}{r_h} + \ln \frac{l_e}{d} - 2 + \frac{2d}{l_e} - \frac{d^2}{l_e^2} + \frac{1}{2} \frac{d^4}{l_e^4} \right];$$

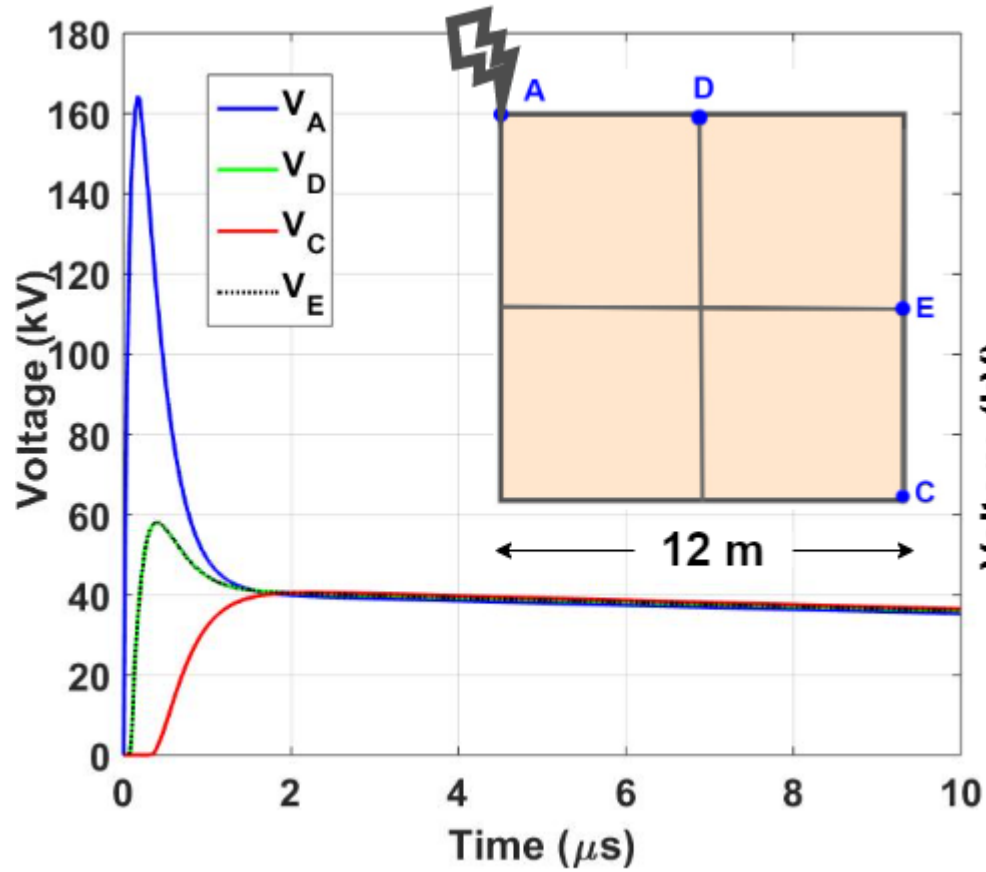
$$C_h = \frac{\mu_0 \varepsilon_0 \varepsilon_r l_e^2}{2L_h}; \quad G_h = \frac{C_h}{\rho_s \varepsilon_0 \varepsilon_r}; \quad R_h = \frac{\rho_c}{\pi r_h^2}$$

Lumped parameters	grounding grid
$R_E'$	1300 $\Omega$
$L'$	0,47 $\mu\text{H}$
$C'$	25 pF
$R$	27 $\mu\Omega$

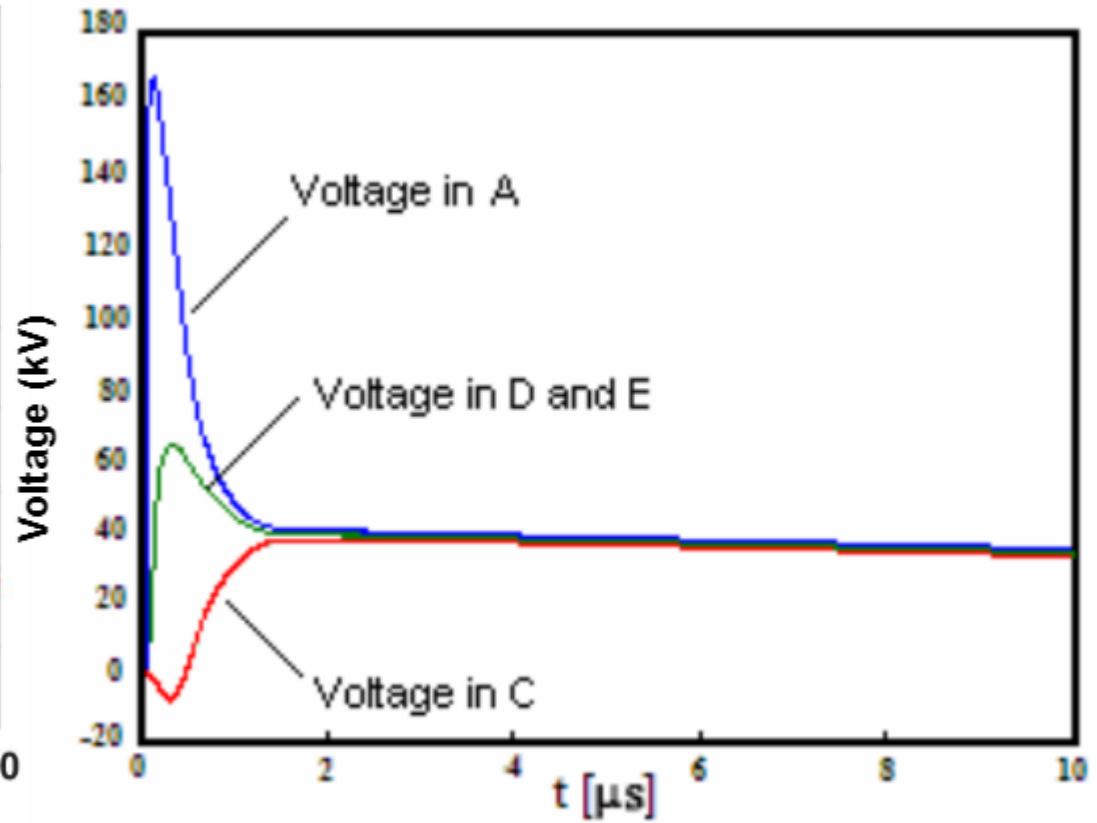
$l_e = 12/50 = 0,24$ ;  
 $N = 50$  pis em cada segmento



# Tensões nos pontos A, B, E e C



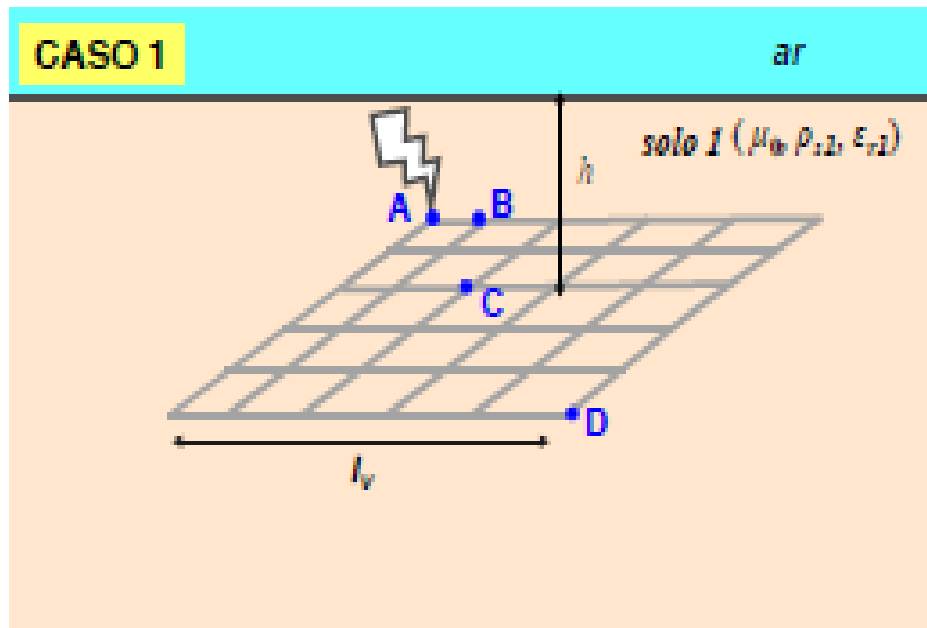
(a)



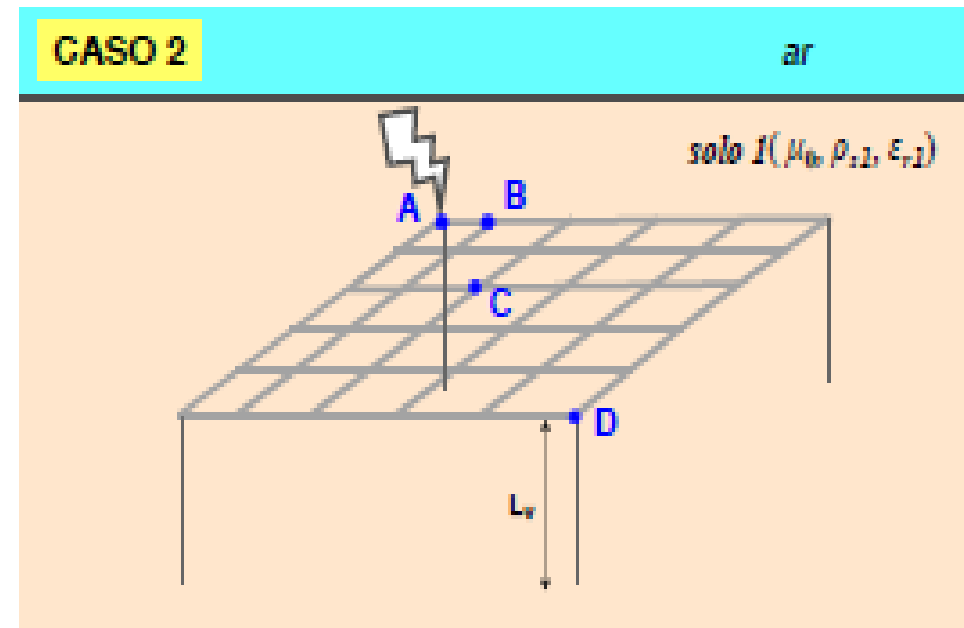
(b)

# Malha com hastes verticais

- Malha de 30x30m
- 4 hastes verticais de 12 m-Circuito obtido pelo VF;
- Condutores horizontais modelados por 30 circuitos pis.



(a)

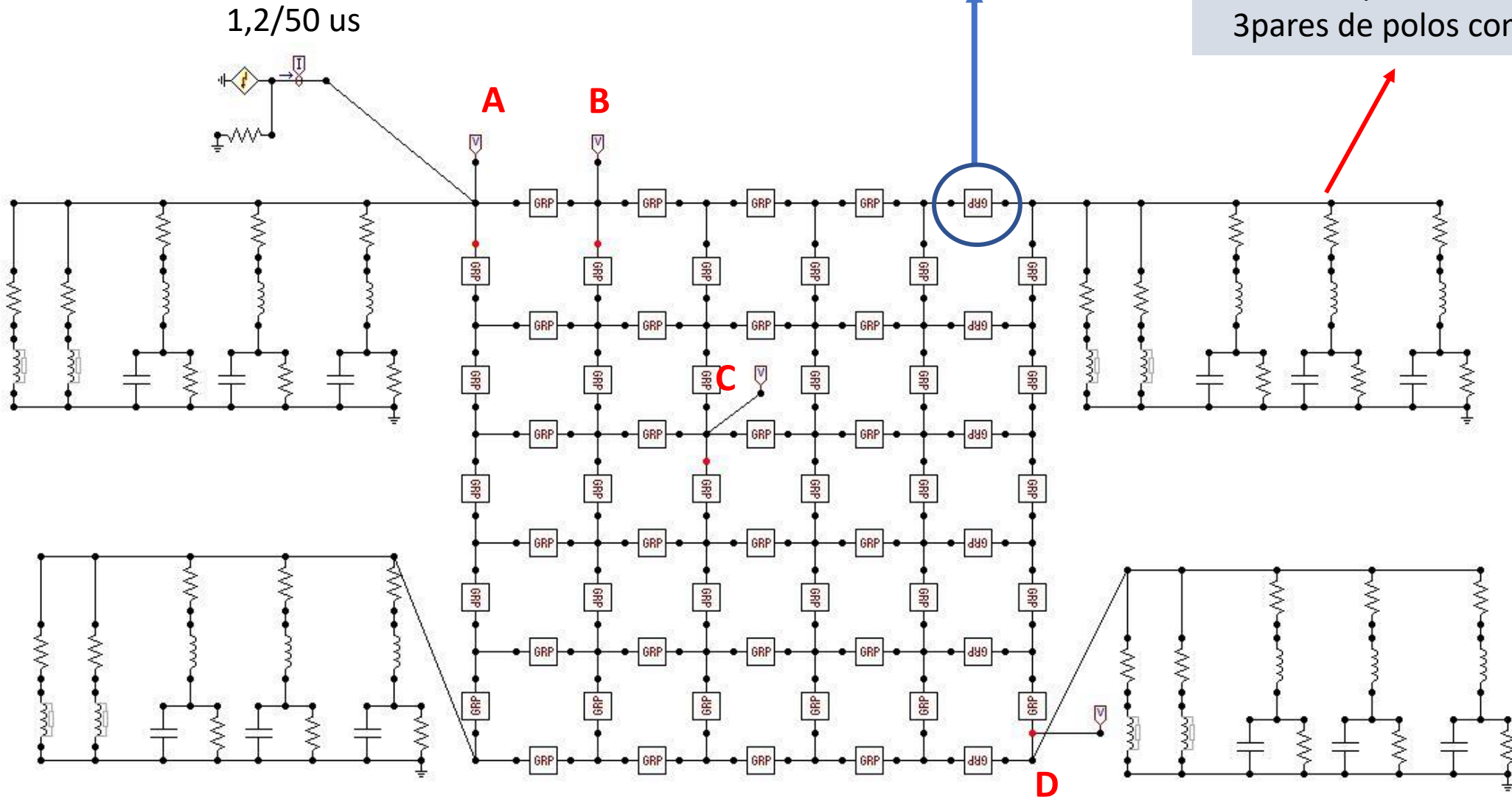


(b)

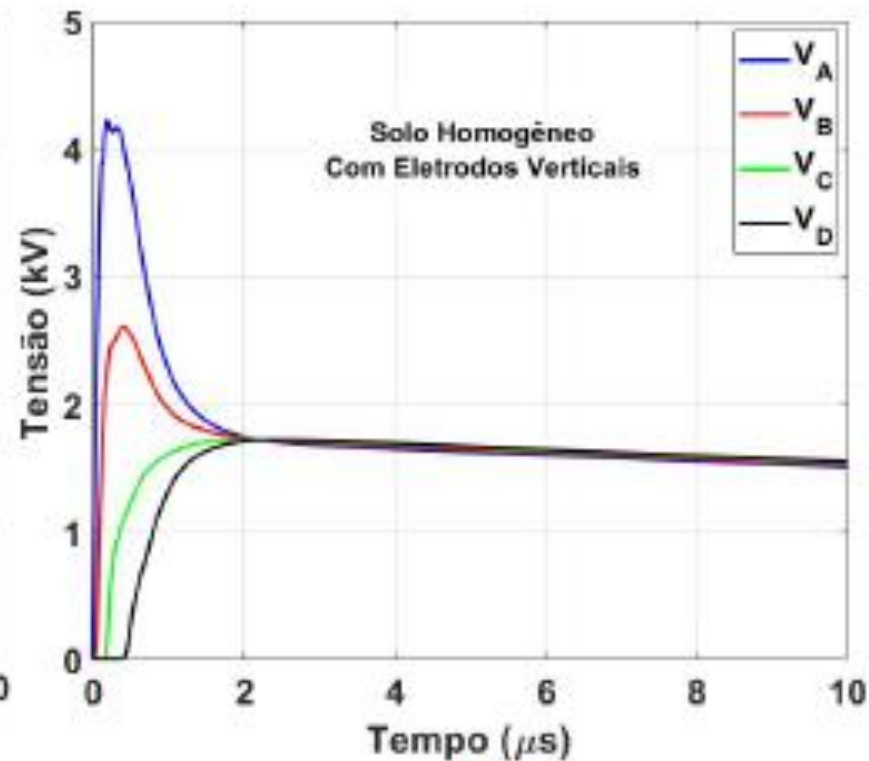
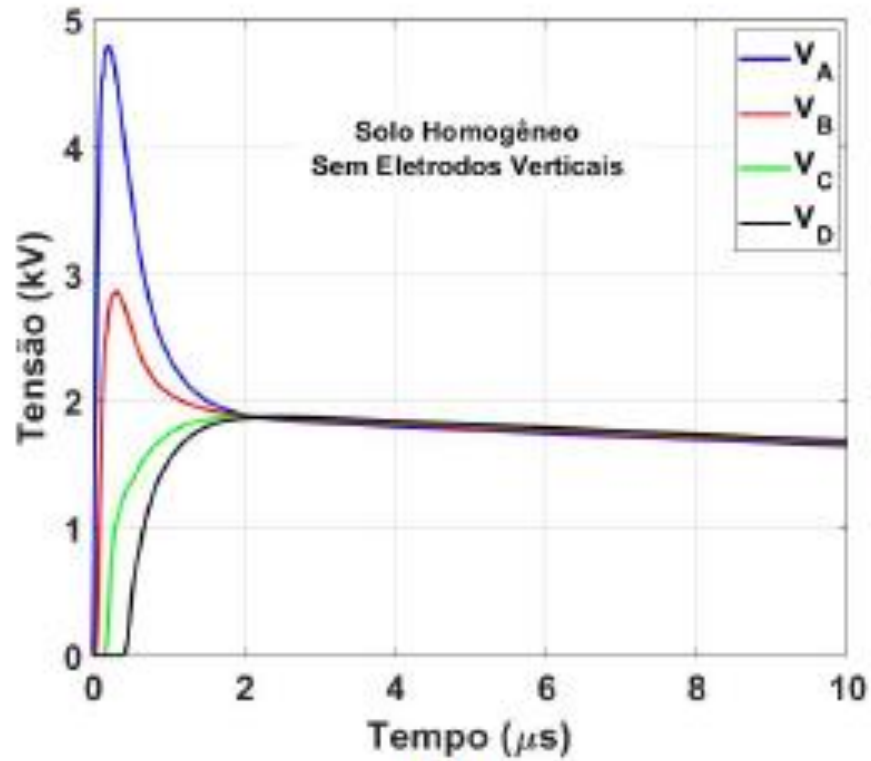
# Circuito da Malha no ATP

Comprimento de 30 m  
Cada grupo-6m com 6 pis

Haste vertical de 12 m,  
circuito obtido pelo VF  
2 polos reais  
3 pares de polos complexos

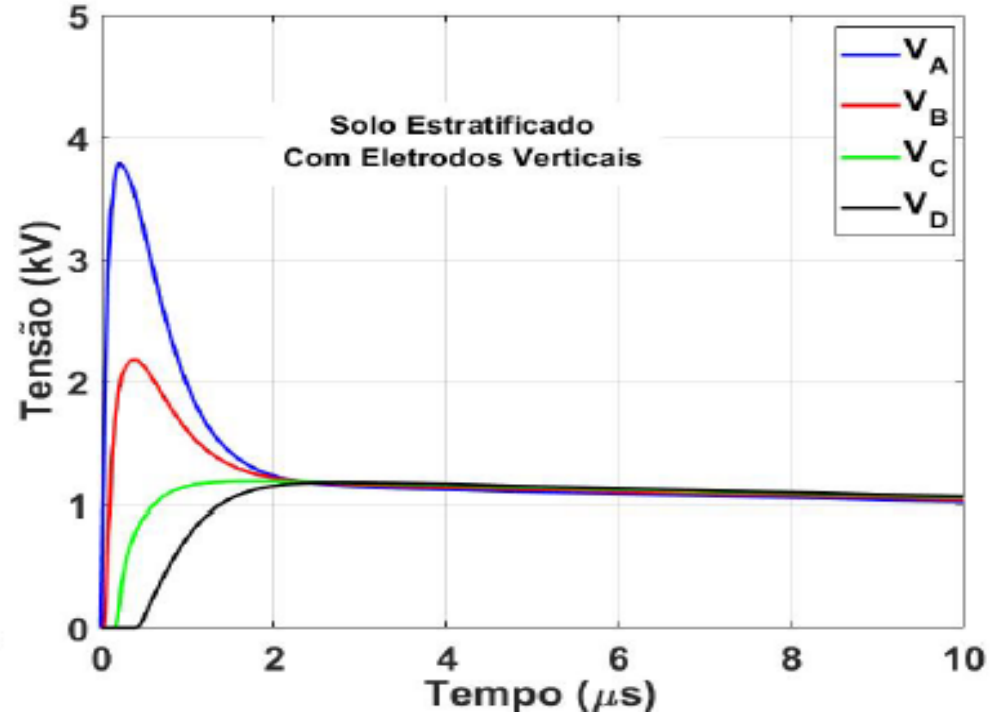
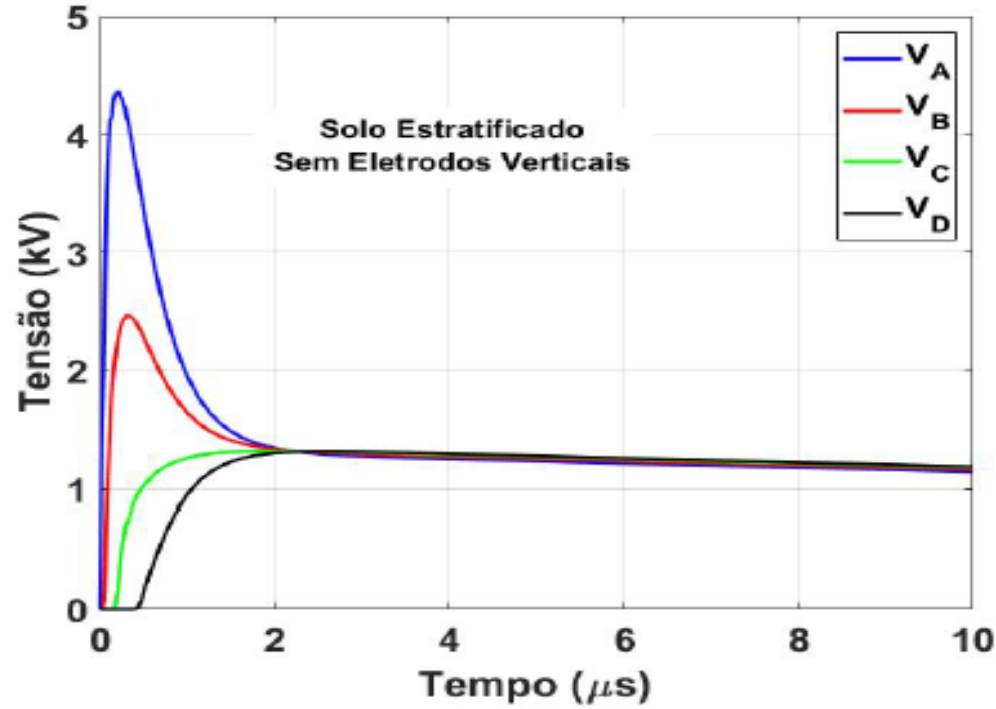


# Resistividade de 1.000 Ohm



Solo Homogêneo			
Nó	Caso 1	Caso 2	Red.(%)
A	4.83	4.225	12.5
B	2.87	2.60	9.40
C	1.87	1.72	8.0
D	1.87	1.72	8.0

# Resistividade de 700 Ohmm



Solo Estratificado		
Caso 3	Caso 4	Red.(%)
4.36	3.80	12.85
2.47	2.18	11.75
1.32	1.18	10.60
1.32	1.17	11.33



# Conclusões

- Os resultados mostraram que quando as hastes verticais são inseridas na malha de aterramento enterrada em um solo homogêneo, o GPR e as tensões nodais são reduzidas, sendo que essa redução é mais acentuada para o GPR no ponto de injeção de uma corrente do tipo onda rápida.
- Para o solo estratificado, a redução do GPR e nas tensões nodais tornam-se mais significativas, uma vez que a resistividade equivalente obtida para tal configuração das camadas é menor do que a resistividade do solo homogêneo.
- Como vantagens do modelo a parâmetros concentrados, novos arranjos para malhas de aterramento de topologia complexa em solos estratificados podem ser analisados usando o modelo a parâmetros concentrados em diversas configurações de solo.

# Recomendações

- <https://www.youtube.com/watch?v=zHRjuOIMs1c> (Universidade da Elétrica)
- Artigos/Teses

## Electromagnetic Transient Modelling of Power Transmission Line Tower and Tower-Footing Grounding System

Thesis Full-text available January 2020

## On High-Frequency Circuit Equivalents of a Vertical Ground Rod

Leonid Grcev, *Senior Member, IEEE*, and Marjan Popov, *Senior Member, IEEE*

## The Transmission Line Modeling Method to Represent the Soil Ionization Phenomenon in Grounding Systems

Daniel S. Gazzana<sup>1</sup>, Arturo S. Bretas<sup>1</sup>, Guilherme A. D. Dias<sup>1</sup>, Marcos Telló<sup>2</sup>, Dave W. P. Thomas<sup>3</sup>, and Christos Christopoulos<sup>3</sup>

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# Aula 04

- Modelagem de malhas;
- Malhas interconectadas;
- Malhas em solos estratificados;
- Potencial de passo e toque;